Volume 53 June-July 1958 Number 4

Economic Geology

and the

Bulletin of the Society of Economic Geologists

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PUBLISHED SEMI-QUARTERLY

Six Dollars Fifty Cents a Year, One Dollar Twenty-five Cents a Copy

THE ECONOMIC GEOLOGY PUBLISHING COMPANY

Printed by Lancaster Press, Inc., Prince and Lemon Streets, Lancaster, Pa.

Entered as second-class matter, March 30, 1906, at the Post Office at Lancaster, Pa., under the Act of Congress of March 3, 1879

Economic Geology

and the

Bulletin of the Society of Economic Geologists

Issued Semi-Quarterly and sent to subscribers on or about the following dates:
February 1, March 15, May 1, June 15, August 1, September 15, November 1, December 15.

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Indexed in the Industrial Arts Series.

LANCASTER PRESS, INC., LANCASTER, PA.

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ECONOMIC GEOLOGY

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BULLETIN OF THE SOCIETY OF
ECONOMIC GEOLOGISTS

VOL. 53 JUNE–JULY, 1958 NO. 4

GEOLOGY OF THE MT. LYELL MINES, TASMANIA[1]

M. L. WADE AND M. SOLOMON

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ABSTRACT

The Mount Lyell Mines, discovered in 1883 and first worked unsuccessfully for gold, have, since 1896, produced 40 million tons of ore averaging 1.43% Cu., and have 45 million tons of 0.73% Cu. in reserve. The chief ore minerals are chalcopyrite, bornite, and pyrite and the host rocks, known as the Lyell Schists, are a variable series of quartz-chlorite-sericite schists.

[1] Published with the permission of the Mt. Lyell Mining and Railway Company, Limited.

Mineralization is centered at points of intersection of the longitudinal, deep-seated Lyell Shear and cross-cutting E–W and NW faults.

Detailed and regional mapping of stratigraphy and structure indicates that the host rocks, the Lyell Schists, are largely altered Cambrian eugeosynclinal volcanics and sediments (the Dundas Group) and, to a lesser degree, altered siliceous Ordovician conglomerates (the Owen Conglomerate).

INTRODUCTION

THE Mount Lyell Copper Mines are located on the West Coast of Tasmania, sixteen miles inland from the Southern Ocean (Fig. 1). They are in an exposed position on the western side of the West Coast Range between 1400

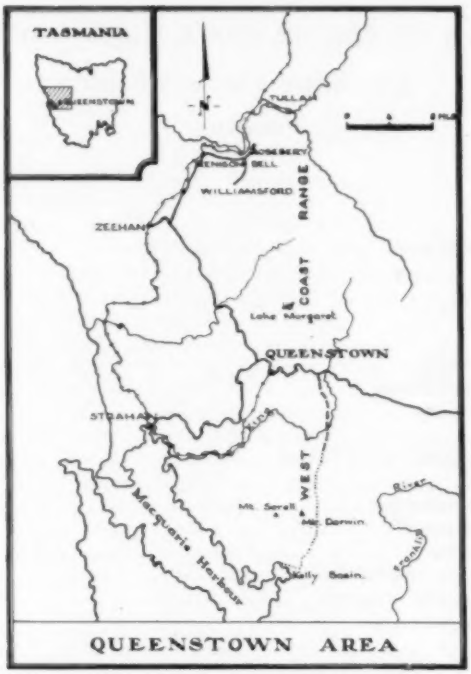


FIG. 1

and 1800 feet above sea-level. The mining township of Queenstown is about one mile to the south-west, in the Queen River Valley, about 500 feet above sea-level. Access to Queenstown is by road from Hobart or Launceston, a distance, in either case, of 158 miles over rugged mountain ranges; by rail and road from Burnie via Zeehan; or by sea to the port of Strahan, thence to Queenstown by rail or road. Cold winds sweep in from the sea and rain

falls in every month of the year, the average annual rainfall at Queenstown being 100 inches and at the mines 119 inches.

The mines have produced a total of 40,000,000 tons of ore containing 574,000 tons of copper, 18,000,000 ounces of silver and 680,000 ounces of gold. Nine separate mines have contributed to this total, of which North Lyell has yielded 43 percent, West Lyell 33 percent, and the Mt. Lyell Mine 12 percent of the copper. Reserves are published as 45,000,000 tons of 0.73% Cu.

Mining at present is confined to the West Lyell Open Cut and involves the removal of the largest combined tonnage of ore and waste of any metalliferous mine in Australia, over 4 million tons of material being mined annually, while in the near future, ore production will reach 2 million tons per annum. The ore now mined contains approximately 0.7% Cu, 9.5% pyrite, with a small though significant amount of gold and silver. Published reserves are sufficient to prolong the life of the open cut mine for a little over 20 years, making a total of about 85 years for the field. In addition there are substantial underground ore reserves but all the mines are closed at the present time. The copper ore is concentrated by flotation, reduced by smelting, and electrolytically refined to pure cathode copper in the Company's works at Queenstown.

The Mount Lyell Mining and Railway Company possesses its own railway system connecting the reduction works with the port of Strahan, where it joins the Tasmanian railway system. It also possesses a hydro-electro system powered from Lake Margaret, 6 miles north of Queenstown, where rainfall is 146 inches per annum.

GENERAL HISTORY

The Mount Lyell Mine was discovered in 1883 by prospectors who were searching for gold. After being worked unsuccessfully for gold, the Mt. Lyell Mine was developed as a copper mine and by 1891 several other mines had been discovered in the vicinity. A bonanza of copper and silver enabled the Mt. Lyell Company to establish a railway and smelters, and in 1896 copper matte was produced by direct pyritic smelting of the Mt. Lyell ore. Production has been continuous ever since.

The rich North Lyell orebody discovered in 1897 encouraged the North Lyell Company to build its own railway to Kelly Basin and its Smelters at Crotty, but treatment methods failed and the future of the field became assured only when the two major companies amalgamated in 1903.

Scores of leases were pegged out around Mount Lyell but few payable orebodies were found and only four early companies worked at a profit. Gradually leases were abandoned or sold to the Mount Lyell Company which now holds the entire field in one consolidated lease.

PREVIOUS GEOLOGICAL WORK

The first geological report on the Mt. Lyell mining field was published in 1886 by Thureau (32). This was followed by a number of small reports by Alexander; Daly; Grayson; Haber; Johnston; Lawson; Montgomery;

Muir; Officer, Balfour and Hogg; Peters; Power; Stewart; and Twelvetrees. Gregory made the first comprehensive worthwhile report in 1904 and this was published in 1905 (15); he recognized the ore control as structural and that the orebodies occurred close to a contact between conglomerates and schists, the latter being derived from volcanics and intrusives.

Hills (18) presented a somewhat confused picture of faulting and thrusting and he regarded the schists (known as the Lyell Schists) as derived from pyroclastic rocks underlying the conglomerates.

Nye, Blake and Henderson (22) thought the schists were altered igneous rocks that intruded the conglomerate. They were the first to map the zones of low-grade mineralization.

Edwards (7) made an important contribution to the knowledge of the mineral composition of the Mount Lyell copper ores.

Conolly (6) was the first geologist to map and elucidate the structure as a result of detailed mapping and his work paved the way for a lengthy exploration campaign by diamond drilling. He followed the work of Nye et alia in regarding the Lyell Schists as intrusives.

Alexander (1) presented a general summary of the mine geology, largely based on Conolly's work.

Carey (4) elucidated the regional setting of the Lyell ore deposits and recognized that the host rocks were sediments and volcanics deposited in narrow geosynclinal basins flanking a Precambrian block; he regarded all copper mineralization as controlled by the Lyell Shear.

This general picture was amplified by Bradley (3) as a result of regional reconnaissance mapping and he suggested that the Lyell Shear controlled regional metamorphism and sedimentation besides mineralization.

The authors' work was begun in 1953 and since then the extensive surface exposures of the mining field have been completely re-mapped in detail and about 300 square miles of the surrounding country have been mapped on a regional scale.

PHYSIOGRAPHY

The most striking topographic feature of the area is the line of rugged peaks that form the West Coast Range. They rise from a general plain level of between 700 and 1,000 feet to an average of 3,500 feet above sea-level, with a maximum at Mt. Sedgwick of about 4,000 feet. The mountains lie along a longitudinal belt of rough terrain that is characterized by wide areas of flatly-dipping, hard, siliceous conglomerate. From north to south the peaks are named Mts. Sedgwick, Lyell, Owen, Huxley, Jukes, Darwin, Sorell, and South Darwin, the last named marking the southern termination of the Range.

This long line of mountains is flanked on either side by deep river valleys, the most prominent of which are the King River on the east and the Queen River on the west. The King River is the largest and rises well to the north near Eldon Peak. It flows southward past Sedgwick, Lyell, Owen, and Huxley but then swings westward and passes through a deep gorge between Mts. Huxley and Jukes. It is then joined by the Queen River, flowing

southward, and winds its way along a soft limestone bed until it enters Macquarie Harbour 2½ miles south of Strahan. The King River Valley east of the Range separates the latter from the rugged Central Plateau of Tasmania. West of the Queen River a gently dipping but deeply dissected peneplain surface (the Henty peneplain) slopes westward to the sea.

The ruggedness of the Range has been further accentuated by mountain glaciation both on the western and eastern slopes, and cirques, hanging valleys, ice-smoothed platforms, and other classical glacial forms are abundant. The effects of valley glaciation are also seen in the Comstock and Linda valleys, and along the upper parts of the King River.

Geological control of the topography and drainage is complete. The distribution of the resistant Owen Conglomerate formation has an obvious control over the drainage pattern and the major rivers are confined to the underlying or overlying softer formations. Along the West Coast Range the Conglomerate is folded into a broad anticline with a N–S strike and the softer overlying sediments have been stripped off the higher levels near the fold axis, so that they flank the fold in broad valleys. Thus the West Coast Range more or less marks the fold axis in the Conglomerate and the valleys on either flank are cut in the younger strata. Differential erosion in the younger series of alternating quartzites, shales, and limestones produces further topographical complications. Of special importance is the Gordon Limestone immediately overlying the conglomerate—it is particularly susceptible to erosion and its presence is commonly indicated by wide, flat, marshy valley floors. Much of the King and Queen rivers are cut in this bed. Along the Range it may be said that generally speaking the present topography marks the base of the Gordon Limestone.

Faulting plays no small part in determining topographic form—the steep eastern flank of the Range east of Mts. Sedgwick and Owen owes its origin to strong faulting combined with glacial action. Again, the broad open valleys of Linda and Comstock, though slightly modified by glacial erosion, closely reflect the geological structure. They owe their origin to E–W faulting and in the Linda Valley are preserved remnants of the younger sediments that have been stripped off the rest of the more elevated Range. Again, the strong NW faults that cut across Mts. Owen and Jukes are clearly indicated by the steplike northern faces of both these mountains.

Old peneplain surfaces are clearly visible throughout the area. The oldest is probably the Carboniferous peneplain at about 3,500 feet, on which lie the Permian tillite and dolerite of Mt. Sedgwick. This level is also seen at Mt. Dundas and along the concordant summits of the Range. The other major surface is the Henty peneplain, which slopes westward from about 1,000 feet at the base of the Range to about 500 feet near the coast. It has undergone fairly recent (Late Tertiary?) uplift and is deeply dissected by a youthful drainage system. The levels reflect a post-Paleozoic history of restricted sedimentation, prolonged periods of erosion, and a successive lowering of base level as a result of block faulting stepping up to the east. The major periods of uplift due to faulting were post-Permian (possibly Jurassic), early Tertiary, and late Tertiary (Kosciuskan).

REGIONAL GEOLOGY

The Mt. Lyell Mines lie on a belt of mineralization that extends to the north and south for many miles, from Mt. Darwin to beyond Tullah (Fig. 1). The northern areas are characterized by silver-lead-zinc and silver-lead-copper orebodies (e.g. Rosebery Mines), whereas the southern parts, in which Mt. Lyell lies, are rich in copper minerals. This longitudinal mineralized zone is closely related to regional structure and the localization of the major orebodies along it is controlled by the presence of cross-cutting east-west or north west structures. The orebodies occur in Lower Paleozoic rocks and discussion of the tectonics and sedimentation in the Lyell area is concerned mainly with rocks of this age. Younger strata are almost absent and later structures have little effect on ore occurrence.

The geological history is summarized in Table 1 and Figure 2 gives a generalized geological map of the Lyell locality.

TABLE 1

Recent:	River gravels	
Pleistocene:	Moraines	
Tertiary:	River gravels	
Permian:	Tillite	
	TABBERABBERAN OROGENY	
Siluro-Devonian:	Eldon Group:	Sandstones, quartzites and shales
Ordovician:	Junee Group:	Gordon Limestone
		Owen Conglomerate
		Jukes Conglomerate
	TYENNAN OROGENY—JUKESIAN MOVEMENT	
Cambrian:	Dundas Group:	Graywackes, pyroclastics, lavas and siltstones
	TYENNAN OROGENY—STICHTAN MOVEMENT	
Precambrian:		Quartz mica schists, quartzites etc.

STRATIGRAPHY

Lower Paleozoic sedimentation and tectonics in Tasmania were to a large extent controlled by a relatively rigid Precambrian massif occupying the central, elevated part of the island. Post-Precambrian deposition was largely confined to broad belts flanking this mass (known as the Tyennan Block), which also exerted a profound influence over the disposition of the forces that folded and thrust the strata in the major orogenic periods.

Early in the Cambrian, geosynclinal conditions developed over a wide area of Australia, with the eugeosynclinal environment prevailing in Tasmania and at least part of Victoria. Within this eugeosyncline, there developed a zone of sedimentation flanking the Precambrian core but receiving little or no detritus from it. This sedimentary basin was characterized by local earth movements and volcanic activity, resulting in the deposition of at least five thousand feet of graywackes, lavas, and pyroclastics, which form the Dundas Group (Carey (4)).

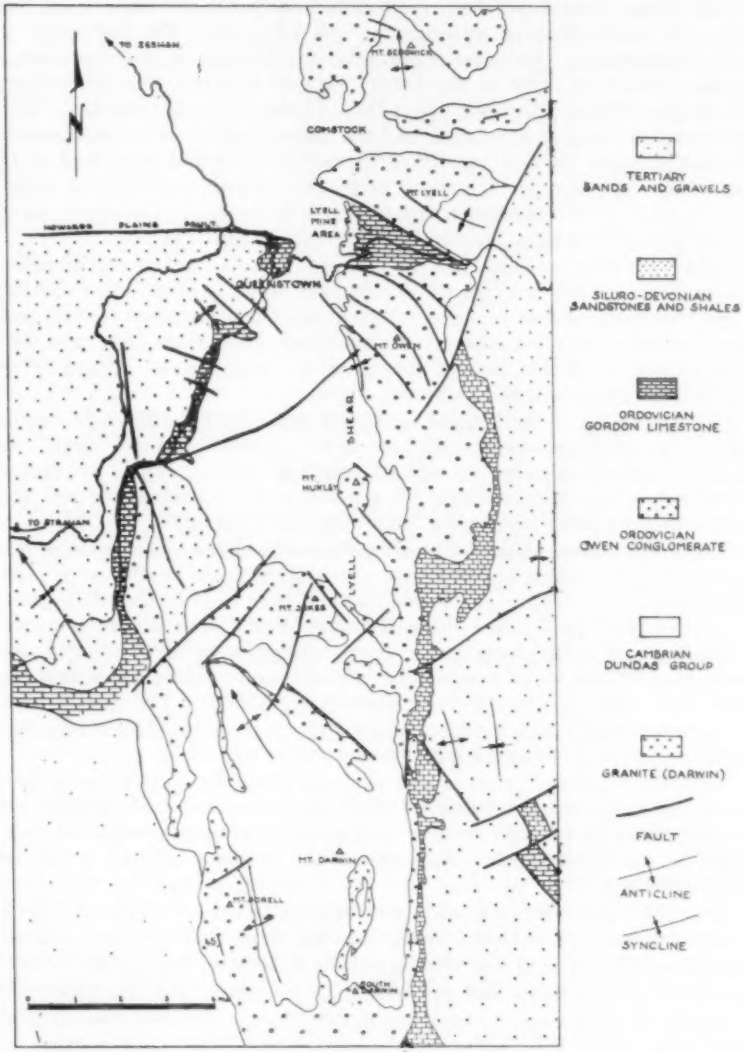


FIG. 2 GENERALISED GEOLOGICAL MAP OF THE QUEENSTOWN AREA

The principal lithologies of this group are graywacke conglomerates of various types; sandstones, both graywacke and quartzose; basic lavas, keratophyres, and associated pyroclastics; and siltstones. The sediments are unfossiliferous near Queenstown but similar lithologies in the type area at Dundas (about 15 miles to the north) contain trilobites and dendroids of Middle and Upper Cambrian age (24). Owing to rapid variations along strike and in vertical succession, and the lack of fossils, it is impossible to establish a useful general succession, so that the formal names used in the succeeding discussion are applicable as rock-terms only and have no significance in time. This realization vitiates much of Bradley's description of the succession in the Dundas Group of the Queenstown area (3a).

The graywacke conglomerates are typical of those formed in eugeosynclinal environments. They are poorly sorted and hence seldom show bedding planes; are composed of a variety of rock types and abundant felspar, indicating conditions of rapid erosion and burial; are of lenticular form; and show rapid changes in pebble content and grain size along strike. Many of the conglomerates may well be of volcanic origin.

The sandstones of the Dundas Group are generally the graywacke equivalent of the conglomerates, though several are commonly fairly "clean" and one, the Miners Sandstone, is a normal quartz sandstone. This bed outcrops prominently along Miners Ridge, 1½ miles east of Lynchford, and has been found a useful marker horizon for "following-out" structure.

Lavas have been recognized at a number of localities and vary from acid to basic in type. Along Lynch Creek, albitized pyroxene basalts occur interbedded with tuffs, breccias, and siltstones and have been termed the Battery Volcanics (3a). In the area of the East and West Queen Rivers, a number of rhyolitic and keratophyric lavas occur, mingled with conglomerates, siltstones etc. These rocks are heavily albitized and slightly chloritized but retain their original texture and are locally amygdaloidal. The igneous rocks are characteristically rich in albite and generally high in Na_2O; it is uncertain whether the soda is of magmatic or metasomatic origin.

Spherulitic "felsites" occur at several points along the Lyell Shear, notably between Mts. Huxley and Darwin. They have the texture of rhyolites and the composition of potassic rhyolites and their distribution is obviously controlled by the Lyell Shear. Analyses of the principal igneous rocks are given in Table 2.

Lavas are associated with tuffs and breccias, some of which are due to "autobrecciation" of the chilled surfaces of the flows, and others to volcanic explosions. In this area and elsewhere it is difficult to distinguish between graywacke conglomerates and pyroclastic agglomerates, and the proportion of volcanics to sediments is impossible to determine. As with other Dundas Group rock types, they grade rapidly along strike into conglomerates or siltstones.

Dark gray finely banded siltstones are encountered at several localities near Queenstown and they form the one easily recognized and unvarying lithologic unit. They are not strictly siltstones but typically consist of finely

TABLE 2

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
SiO_2	48.1	73.44	74.96	70.60	56.80	67.52	51.64	22.12	50.0	45.04	49.4
Al_2O_3	19.0	14.18	13.55	13.31	17.11	11.99	17.32	21.35	17.6	36.68	45.1
Fe_2O_3	11.8	1.46	0.79	1.54	2.12	1.77	5.18	4.74	11.4	0.53	
FeO		0.55	0.71	2.36	5.26	6.81	11.09	32.69	n.dt.	0.23	
MnO	n.dt.	Tr.	0.01	0.05	0.28	0.16	0.12	1.24	n.dt.	Tr.	
TiO_2	0.5	0.33	0.13	0.40	0.35	0.28	0.56	0.45	n.dt.	0.07	
CaO	7.8	nil.	0.16	1.68	4.20	0.12	0.28	nil.	4.4	0.48	
MgO	6.4	0.43	0.48	1.75	3.61	1.22	2.56	6.45	4.7	1.91	
Na_2O	2.2	0.16	2.33	4.44	4.47	0.59	1.02	0.14	6.3	4.40	
K_2O	1.3	8.05	5.57	2.03	2.75	2.73	2.79	nil.	1.8	4.18	
H_2O-	1.8	0.08	0.16	0.06	0.04	0.02	0.06	0.36	4.2	0.32	5.6
H_2O+		1.38	0.86	1.46	2.58	1.95	3.90	9.74		4.32	
S	1.0	Tr.	nil.	0.07	nil.		0.03	nil.		0.04	
CO_2		0.38	0.30	0.73	0.44	3.90	3.27	0.28		nil.	
P_2O_5		0.10	0.05	0.08	0.33		0.16	Tr.			
FeS_2						0.45					
BaO										1.13	
Cu									0.05		
Total	100.0	100.54	100.06	100.56	100.37	99.57	99.98	99.36	100.45	99.65	100.1

I—Average of three analyses of pyroxene basalts by the Mt. Lyell Co. Assay Office in 1954 and one by Scott (31).
II—Intercolonial Spur "felsite." Analyst: Tas. Mines Dept. 1956.
III—Pink granite, South Darwin. Analyst: Tas. Mines Dept. 1956.
IV—Quartz felspar porphyry (sodic rhyolite), West Queen River. Analyst. Tas. Mines Dept. 1956.
V—Felspar porphyry (trachyte) Lake Margaret Tramway. Analyst: Tas. Mines Dept. 1956.
VI—Pink quartz sericite schist, from diamond drill hole West Lyell No. 90 at 1,255 feet. Analyst: Tas. Mines Dept. 1956.
VII—Quartz-chlorite schist, West Lyell open cut. Analyst: Tas. Mines Dept. 1956.
VIII—Chlorite schist "bed," south of West Lyell open cut. Analyst: Tas. Mines Dept. 1956.
IX—Gray schist from West Lyell Tunnel at 50 feet from portal. Analyst: Mt. Lyell Co Assay Dept. 1956.
X—Green "schist," North Lyell Mine. Analyst: Tas. Mines Dept. 1956.
XI—So-called "batchelorite." Analyst: Mt. Lyell Co. Assay Dept. 1905.

alternating bands of shaley quartz silt and quartzose shale. Originally named the Miners Slates by Bradley, they have been re-named Lynch siltstones.

The rock units described above vary rapidly along strike and individual horizons are difficult to follow in the field; mapping is further hindered by the clouding effects of the regional metamorphism that has altered much of the Dundas Group. As a consequence, elucidation of structure is not easy and determination of a stratigraphic sequence with definite thicknesses is virtually impossible. The total thickness of the Dundas Group is probably greater than 5,000 feet but less than 15,000 feet.

Towards the close of the Cambrian period, the Dundas strata were elevated by folding and faulting along a longitudinal zone that more or less parallels the West Coast Range; an important phase of this tectonic activity was west side up movement on the Lyell Shear (Figs. 2, 4). This movement represented the culmination of minor tectonic activity that must have characterized the eugeosynclinal environment; it is known as the Jukesian movement of the

Tyennan orogeny and was probably accompanied by regional metamorphism. The Darwin granite was intruded at this stage, as shown by the presence of granite pebbles in the basal conglomerates of the overlying sediments (Jukes Conglomerate); Bradley (3a), however, interprets these pebbles as being due to Devonian granitization of Cambrian rocks and also pebbles derived from these rocks in the younger conglomerates.

The occurrence of potash-rich and siliceous granite, rhyolite, and felsite along the Lyell Shear zone, and the predominantly less siliceous, soda-rich rocks in the flanking areas, points to strong structural control over volcanic and intrusive activity during the Cambrian and the following Jukesian movement. Bradley (3a) suggests that the potash-rich rocks of the Shear zone owe their origin to granitization processes.

Jukesian folding and faulting resulted in the formation of east-facing escarpments along the line of the West Coast Range mainly as a result of west-side-up movement on the Lyell Shear. Erosion was particularly rapid along this zone and resulted in the deposition of up to 2,000 feet of graywacke breccia-conglomerates in the basin developing between the Lyell Shear and the Tyennan Block. These breccia conglomerates are known as the Jukes Conglomerate (formerly known as the Jukes Breccia but re-named, as most of the pebbles are rounded) and they lie conformably or unconformably on underlying strata. This variation in relationship may reflect the localized nature (probably mainly faulting) of the Jukesian Movement. Jukes Conglomerate probably also developed along the western margin of the elevated zone, though there were probably no fault scarps there. The exact extent of the Dundas Group exposed to erosion at this stage is uncertain but was probably confined to a comparatively narrow longitudinal zone slightly west of the West Coast Range, known as the Dundas Ridge.

When deposition of the Owen Conglomerate commenced in the early Ordovician or late Cambrian, small ridges and islands remained elevated and at least portions of the Dundas Ridge (mainly in the Queenstown area) were only covered in the final phases of Owen Conglomerate deposition. The importance of this feature will be made obvious in the ensuing discussion.

The Owen Conglomerate formation is almost entirely siliceous and is composed either of quartz pebble conglomerates or sandstones. The rounded pebbles and the degree of sorting exhibited by the formation indicate prolonged wave action along old shore lines, a marked and sudden change from the conditions prevailing in the Cambrian period. The Owen Conglomerate is derived almost entirely from Precambrian sources and must mark a relatively sudden emergence of the Tyennan Block, probably as a result of faulting. A conspicuous feature of the Conglomerate is the decrease in grain size upwards through the succession; while the lower beds are coarse pebble conglomerates, the upper beds are mainly sandstones and sandy shales. At the same time, the older strata are restricted to a narrow zone of deposition more or less coincident with the West Coast Range, while the finer and younger members transgress these limits and extend over wide areas of the West Coast.

On a basis of grain size, and to assist in field mapping, the formation has been subdivided as follows:

Upper Owen Conglomerate: Gray or pink sandstones, hematitic shales, and fine conglomerates.

Middle Owen Conglomerate: Gray or yellowish medium and large pebble conglomerates with thin sandy bands and reddish quartzites.

Lower Owen Conglomerate: Very large pebble conglomerates, locally with a sandstone bed.

The formation has been named after Mt. Owen, on which all three members are well developed and exposed. As might be expected with such lithologies, rapid lateral variations are characteristic and correlation of horizons is therefore difficult; it has to be realized that the Lower Owen member of one area is not necessarily the equivalent in time of the Lower Owen in another. The three subdivisions are made purely on general lithological characteristics and therefore do not necessarily have any significance in time. However, the classification holds generally and is most useful for field mapping.

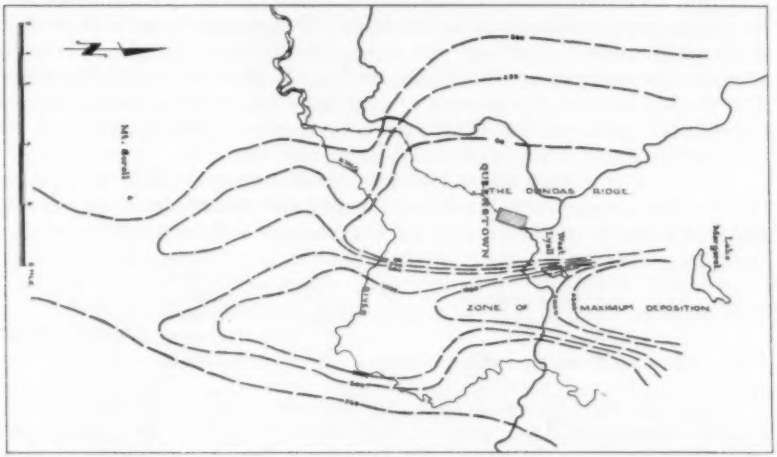


FIG. 3. ISOPACHYTES OF THE OWEN CONGLOMERATE.

It has already been mentioned that sections of the Dundas Ridge were being eroded during Owen Conglomerate deposition; therefore it is to be expected that fringing these elevated sections there would be a narrow zone of largely Dundas-type detritus and that this would merge to normal quartzose Owen sediment. Exposures near Queenstown and particularly at South Darwin confirm this reasoning. The Dundas fringe is narrow, for the softer graywacke sediments and volcanics were unable to survive the rigorous wave action for long.

The generalized distribution of the Owen formation is shown by the isopachytes of Figure 3. The thickness increases northward from South Darwin, reaching a maximum measured thickness of 2,600 ft. on Mt. Lyell

and possibly increasing towards Mt. Sedgwick. The isopachytes clearly show the extent of the Dundas Ridge towards the close of Owen Conglomerate deposition, the remainder of the Ridge to the south being submerged in about Middle Owen times.

A few poorly preserved brachiopods and gastropods, and several types of tubular casts, have been found in the Owen Conglomerate, mainly in the upper beds, but insufficient material has been collected for accurate age determination. The formation is presumed to be late Cambrian or early Ordovician, from evidence gathered near Rosebery and on the north coast of Tasmania: in the Huskisson River, middle Upper Cambrian trilobites have been found in the Dundas Group, and at Caroline Creek sandstones overlying the Owen Conglomerate contain Arenigian trilobites.

Deposition of siliceous conglomerates was succeeded by the Gordon Limestone, a characteristic formation that outcrops over wide areas of the West and North West coasts of Tasmania. In the Lyell area it varies from dark blue-gray limestone, through limestone with shale bands, to dark shales with limestone lenses, and non-calcareous shale. Shaley zones weather to a characteristic blue-black "pug" or clay. The limestone weathers more rapidly than contiguous formations and hence tends to occur in swampy valley floors. This marked contrast in resistance to erosion of adjacent strata partly explains the rugged nature of the West Coast topography. The thickness of the Gordon Limestone varies between 1,000 and 2,000 feet.

Limestone deposition was followed by the alternations of shale and quartzose sandstone comprising the Eldon Group; the formations of this Group and their approximate thicknesses are shown in the following table:

Bell Shale	+7,000 ft.
Florence Quartzite	1,800 ft.
Keel Quartzite, Shale and Limestone	1,200 ft.
Amber Slate	900 ft.
Crotty Quartzite	900 ft.

Gill (12), and Gill and Banks (14), have described the Eldon Group at Zeehan in some detail and most of their findings apply in the Queenstown area. Gill describes the age of the Group as Silurian to Devonian, there being some doubt as to the position of the basal members; he suggests there may be a disconformity below the Crotty Quartzite. The formations of the Group show an alternation of rock types with a gradual reduction in contrast between propinquent sediments; an overall reduction in grain size of the arenaceous members from bottom to top; and a predominance of silica, even the shales being essentially siltstones. Members of the Eldon Group outcrop in synclinal basins on either side of an anticlinorium which coincides with the West Coast Range. They show only local copper carbonate staining and gold mineralization.

Eldon sedimentation was concluded in the middle Devonian by a period of violent tectonic activity, metasomatism and sulfide mineralization, known as the Tabberabberan Orogeny. During this phase all the important structures of the area were formed, and all the major orebodies emplaced.

The Tabberabberan Orogeny was followed by a prolonged period of erosion extending through the Carboniferous, during which the area was planed almost to sea level. Sedimentation commenced in the early Permian and continued through to the Triassic period, during which time an unknown thickness of sandstones, shales, and tillite were deposited. The only deposit of this age near Queenstown is the tillite on Mt. Sedgwick, which rests in a shallow depression in the Carboniferous erosion surface.

Permo-Trias sedimentation was succeeded by extensive intrusions of dolerite, which spread out as thick sills in the horizontal Permian sediments. The remnant of one of these intrusive bodies covers the tillite on Mt. Sedgwick.

Dolerite intrusion was followed by block faulting with large throw, generally east side up. The presence of Permian tillite at 3,500 feet on Mt. Sedgwick, and also a few hundred feet above sea level at Strahan, is due to this period of movement. Faults of this period were probably situated near to the present coastline and possibly west of Mt. Sorell; they have a N–S or NNW trend.

The prolonged period of erosion which followed this elevation reduced the area west of the West Coast Range to the peneplain that is clearly visible today; it is known as the Henty peneplain and is broken here and there by monadnocks of Lower Paleozoic rocks.

This Mesozoic (?) peneplanation was interrupted in the early Tertiary by a further period of block faulting, which resulted in a general uplift of the Range and Henty peneplain in the order of 500 feet.

During the Tertiary, the area now occupied by Macquarie Harbour was depressed by faulting and received several hundred feet of lacustrine sands, gravels, shales, and lignitic earths; these are known as the Macquarie beds. Late in the Tertiary, the erosion was further rejuvenated by uplift due to block faulting; this movement might be correlated with the Kosciuskan epoch of the mainland of Australia.

The final major event in the geological time scale was the Pleistocene glaciation, which affected the higher parts of the West Coast Range and some of the larger river valleys. Moraines, cirques, ice-smoothed pavements, and U-shaped valleys testify to the work of the Pleistocene ice. Of particular interest is the King glacier, which flowed down the King River valley, and forced its way up many of it's tributaries against the natural drainage direction. The Comstock and Linda valleys provide examples of these ice tributaries and at the head of each there are extensive deposits of till, with some varved clay, indicating the presence of ice-dammed lakes. The level of each lake was controlled by the elevation of the watershed between the King and Queen drainage systems and overflow from the lakes drained west towards the Queen River. At no stage did the ice sheet cross either the Lyell-Owen, or the Lyell-Sedgwick divides. The glaciers of the higher parts of the West Coast Range generally melted below 2,000 feet, though a few tongues descended to 1,500 feet. Associated glacial features are well exposed on the sheltered eastern slopes of Mts. Sorell, Jukes, Owen, and Sedgwick; and also at Lake Margaret, where a large arcuate moraine extends out from the Lake on the lower western slopes of the Range.

Although much of the ruggedness of the area is due to glacial erosion, modification of pre-Pleistocene topography by glacial agencies is only of minor significance.

STRUCTURE

The complex structures observed in the Lyell area today are largely related to the Tabberabberan Orogeny of mid-Devonian age. This period of violent upheaval marked the culmination of minor earth movements that characterized Lower Paleozoic stratigraphy on the West Coast.

The distribution of the copper orebodies in the Lyell district is obviously related to structural features, and these, therefore, have received considerable attention. Of particular importance, too, is the understanding of the history of movements along some of the major structures that have influenced the course of Paleozoic sedimentation.

The major factors controlling the development of the structural pattern have been:

(a) forces acting from the SW;

(b) the presence of a relatively rigid massif to the east;

(c) the increasing thickness of the geosynclinal sediments westwards from the margin of the massif.

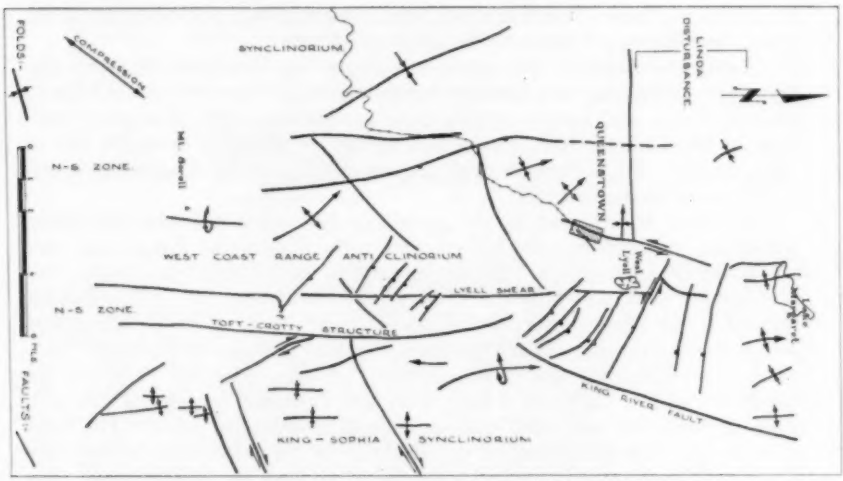


FIG. 4. PRINCIPAL STRUCTURAL ELEMENTS IN THE QUEENSTOWN AREA

SW–NE compression resolves into components aligned parallel and perpendicular to the margin of the Tyennan Block, resulting in E–W compression of the geosynclinal sediments and shearing west side north. This combination of shearing couple and compression (mainly from the west) forms the background to the understanding of the structures flanking the block. The

gradually waning influence of the latter is expressed in variations of the structural pattern moving west of the West Coast Range.

The principal structural elements are as follows (Fig. 4):

(a) The N–S West Coast Range anticlinorium, the King Sophia synclinorium, and related secondary folds.

(b) The N–S Lyell Shear and the Toft-Crotty structure.

(c) The NW fault-folds and NW schistosity.

(d) The Linda Disturbance.

(e) The NE Faults.

The West Coast Range anticlinorium, with its flanking synclinoria, is the major structure of the area, upon which all other features are superimposed. It has a N–S trend with the axis passing to the east of Queenstown and it is markedly asymmetrical, the secondary "drag" folds showing vertical or overturned and commonly severly attenuated eastern limbs, and relatively flat, undisturbed western limbs. It expresses the squeezing of the geosynclinal sediments against the rigid craton by east-directed forces. The King-Sophia synclinorium is wedged in between the West Coast Range anticlinorium and the Tyennan Block (Fig. 4).

The Lyell Shear is an important N–S feature parallelling the Range from Comstock to South Darwin. It is associated with local overturning and attenuation, with granitization and metallization. Its points of conflict with cross-cutting structures are foci for the deposition of sulphides. From Comstock to Mt. Huxley it flanks the western edge of the Range, but from Huxley to South Darwin it hugs the eastern side; its trend is best indicated by the line of mineral occurrence along its length, for, with few exceptions, these lie on a narrow N–S belt from Comstock to Prince Darwin (Fig. 5).

Movement on the Shear has been west-side-up and north, combining vertical and transcurrent movement. It has been mapped as an intermittent zone of overturning and faulting, varying in its surface expression and locally absent. This is due in part to offsetting of the structure by tear movement on NW faults and partly due to variation of surface expression induced by varying depths to bedrock, and changes in the physical properties of the overlying sediments; in depth it is probably a fault.

The main Shear movement took place during the Tabberabberan Orogeny, but there is evidence to show that it was an active structure at several stages in Lower Paleozoic history. Local unconformities in the Owen Conglomerate along the Shear line and paleographic evidence indicate that the fault has been an active one, probably since Precambrian times. Its control over the distribution of the Owen Conglomerate near Queenstown is of the utmost significance in discussing the origin of the ore hosts at Lyell.

There are other N–S zones of attenuation and faulting akin to the Lyell Shear (e.g. the Toft-Crotty structure), and these also probably were active at several stages during the Lower Paleozoic.

The NW faults are important structures that have a strong influence on ore occurrence. They are essentially asymmetrical, NE facing folds in which the steep limb has been faulted out; hence the term fault-folds. The down throw is to the north and they swing in strike from WNW to NNW. They

are cognate with the Lyell Shear and interplay with the latter structure to produce locally unique developments. In places the Lyell Shear drags the NW folds to N–S trend (by west side north movement); elsewhere the NW faults appear to displace the Shear. They reach their greatest development in the Lyell area, where they show certain anomalous features; the faults swing to WNW trend and near Mt. Lyell and Comstock they face and throw

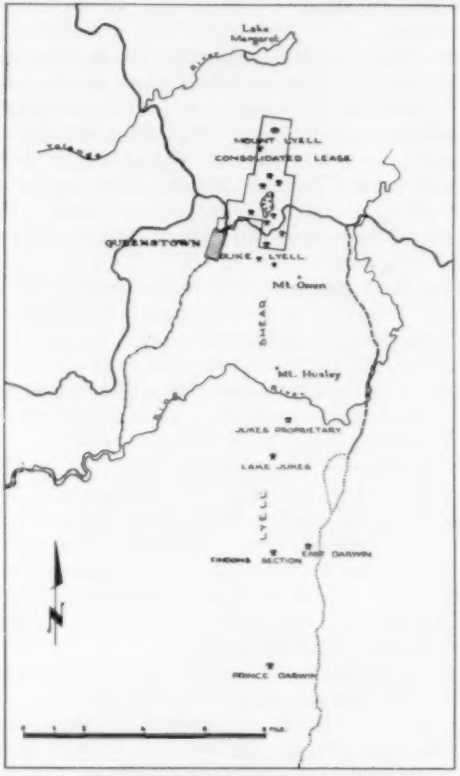


FIG. 5. DISTRIBUTION OF COPPER OCCURRENCES IN QUEENSTOWN AREA

down to the south. This produces a crude WNW rift valley structure (Fig. 10b) in which the rocks are more intensely plicated and faulted than elsewhere; this structural pattern reflects the influence of the Linda Disturbance, an E–W or WNW zone of faulting that may be traced for many miles east and west of the range. The Howards Plains Fault shown in Figure 2 is part of the Linda Disturbance. All the large, rich, copper orebodies of the Lyell area fall within the boundaries of this cross-cutting feature. Recognition of the

presence of major E–W zones that influence ore deposition has facilitated exploration in adjacent areas—for instance, a crudely formed zone of N and S facing structures may be recognized between Mts. Jukes and Huxley, and this provides a target for future exploration.

The NW faults tend to occur mainly in the competent, massive Owen Conglomerates, for in the softer, more yielding Dundas rocks, pressure is relieved by development of schistosity with NW trend.

Tensional faults relating to the N–S shearing couple and SW compression are developed to a limited degree throughout the area. They generally show a small vertical throw, south side up. They appear to be of minor significance, though Bradley (3b) regards them as major factors in ore control.

Metamorphic Rocks

The metamorphic rocks are variable quartz sericite and quartz chlorite schists, commonly showing relict sedimentary structures, and red ferruginous clays, derived from the Gordon Limestone. The schists, known locally as the Lyell Schists, outcrop over the western slope of the Lyell-Owen divide and abut against the sedimentary rocks more or less along the divide. The schists represent part of the Owen Conglomerate, the Jukes Conglomerate and part of the Dundas beds but considerable difficulty is experienced in ascertaining the original nature of much of the schist series.

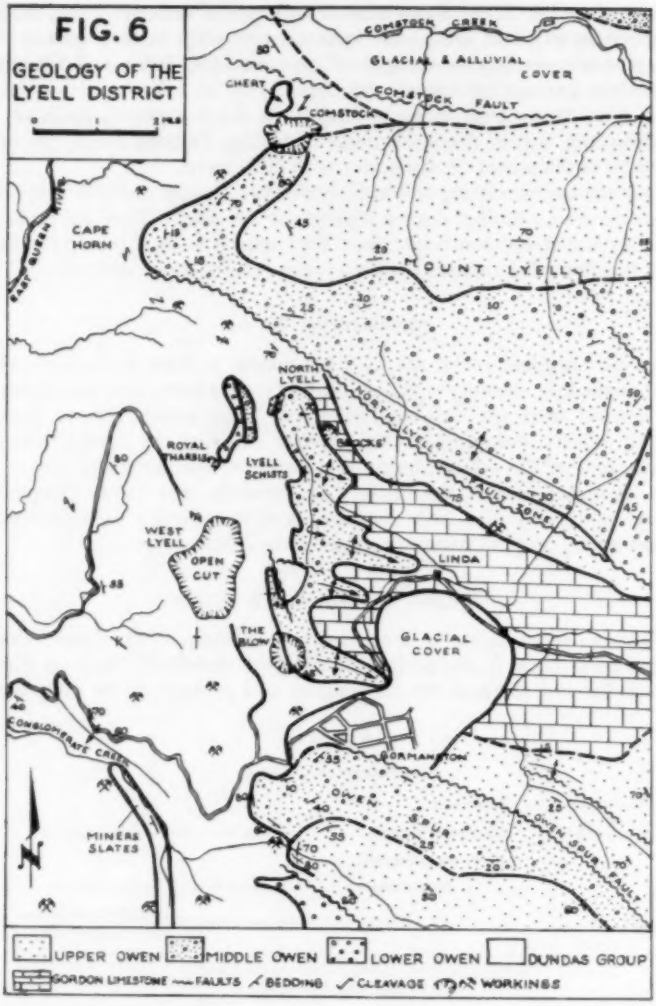
GEOLOGY OF THE LYELL MINES

The rocks outcropping in the immediate vicinity of the Lyell mines are summarized in Table 3; the geology of the Lyell district is shown in Figure 6, and more detailed plans of the topography and geology of the mine area are

TABLE 3

SEDIMENTARY ROCKS

Pleistocene:	Moraines	
Ordovician:	*Gordon Limestone*:	Black shale and some Limestone
	Owen Conglomerate:	
	Upper Owen:	*Pioneer Beds*: Gray sandstone
		Variable sandstone and conglomerate
		Chromite quartzite and conglomerate
		Haulage Unconformity
		Chocolate sandstone with hematite beds
	Middle Owen:	Yellow conglomerates
		Red sandstone or alternating conglomerate and sandstone.
	Lower Owen:	Coarse pebble conglomerate with a red sandstone horizon.



shown in Figures 7 and 8 respectively. Many of the rock-unit terms have only local significance and are adopted merely to assist in field mapping and description.

Sedimentary Rocks

Owen Conglomerates.—The *Lower Owen Conglomerates* are typically coarse siliceous conglomerates, with large pebbles. The pebbles are mainly

quartz, quartzite, chert, and quartz schist and show a high degree of rounding whereas the matrix is gray or pink quartz. Locally, boulders of quartzite and quartz reach a diameter of 2 feet, and the conglomerates are massive and poorly bedded. In the North Lyell Tunnel, 4,900 feet from the portal, a pink sandstone several feet thick occurs in typical Lower Owen Conglomerate and this horizon appears to have been encountered in deep bores of this vicinity. Conolly (6) regarded this as a potential ore horizon but the recent work has failed to substantiate this view.

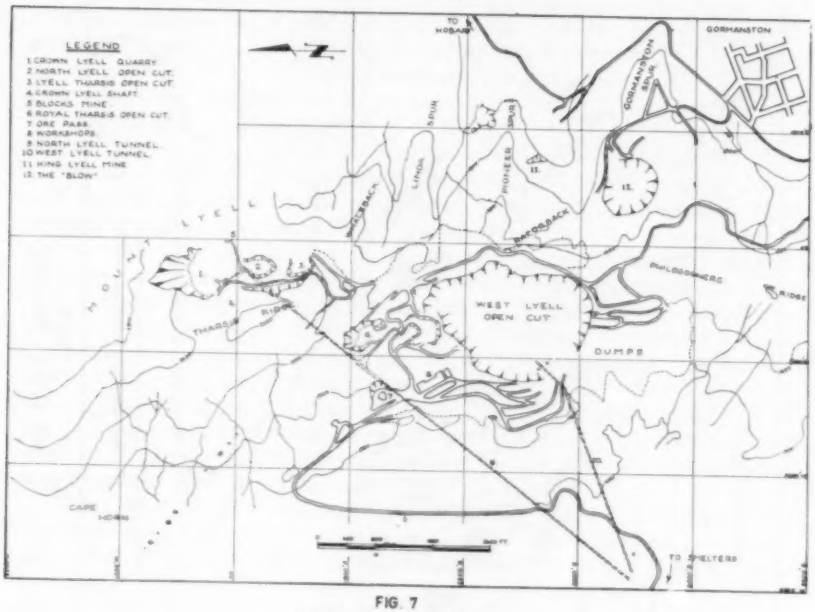


FIG. 7
MT.. LYELL TOPOGRAPHY

The *Middle Owen Beds* are a variable series of large pebble conglomerates and red quartzites. Over Mts. Lyell and Owen, and on the Razorback ridge, a clear cut division into two units is possible; an upper gray-yellow conglomerate and a lower red quartzite, with individual thicknesses varying considerably. However, near the Tharsis ridge, conglomerates and sandstones are interbedded, and near Comstock it is impossible to apply the two-fold subdivision. Figure 9 demonstrates the variability of the Owen formation.

The Middle Owen Conglomerate is a yellowish large-pebble quartz conglomerate with thin sandy beds; it grades upwards through finer conglomerates to the Chocolate Sandstone, but shows a sharp change at its base to red quartzite. On the Razorback ridge it is about 450 feet thick and contains coarser bands of unusual type. These are somewhat poorly sorted, lenticular,

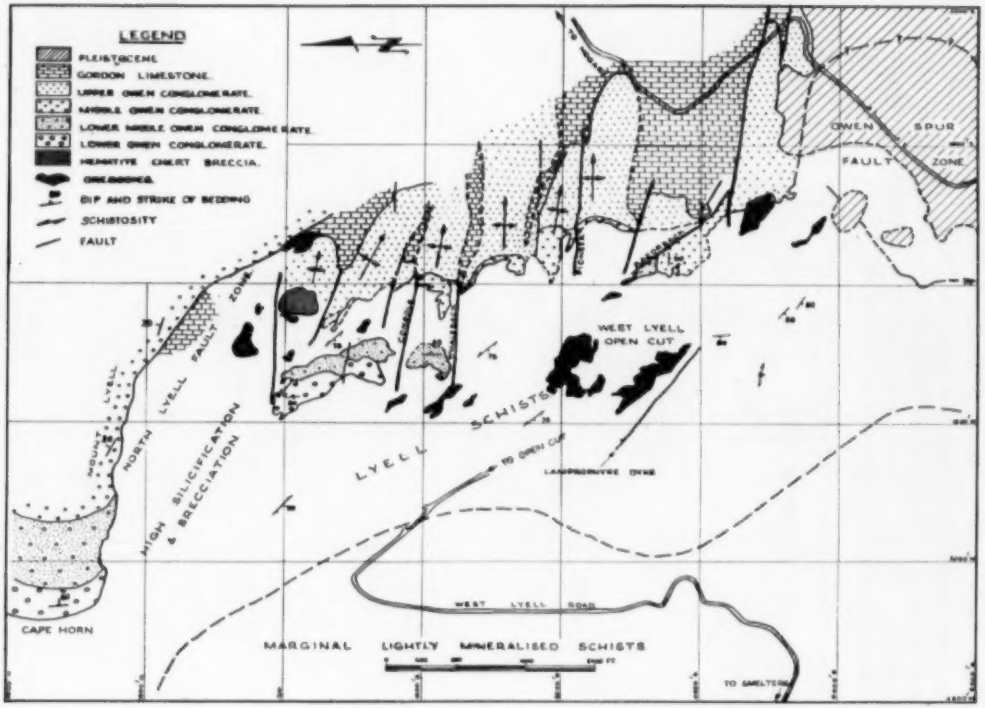


FIG. 8
MT. LYELL GEOLOGY

and composed not only of the customary rounded quartzose pebbles, but also of sub-angular fragments of pink sandstone and hematite, and a few conglomerate pebbles; this rock type is known locally as hematite conglomerate. At 4650S/640E, two sandstone dikes, averaging 3 inches in thickness and up to 25 feet in length, cut across the bedding at right angles. They probably represent fissures developed in the partially lithified conglomerate during Haulage movement and filled with re-worked Chocolate Sandstone. The Middle Owen Conglomerate horizon is important as in it the most important orebodies occur (e.g. North Lyell and the Mt. Lyell Mine).

The underlying red quartzite is well exposed on Mts. Owen and Lyell and on the Razorback. It is blocky but very thinly bedded, and has the grain size of a coarse sand. It is more resistant to metamorphism than the conglomerate facies, probably due to its finer grain, and remnants of quartzite are common in the adjacent schist up to 600 feet from the contact. On the Tharsis ridge, the lower half of the Middle Owen beds are exposed but instead of the red quartzite, lenticular bands of coarse hematite conglomerate alternate with thin beds of red sandstone showing cross-bedding and current scouring. In some places the sandstone facies dominates, in others the beds are almost entirely conglomerate. These beds suggest unstable conditions of deposition, probably near a shore rich in ferruginous material. Further variation in the Middle Owen lithology is seen at Comstock; at Cape Horn the typical conglomerate and underlying sandstone are well developed, but passing towards Comstock this sub-division is lost and the Middle Owen beds thin out and almost disappear near the mine. Once again, the orebody near the surface occurs along the strike of the upper Middle Owen. At 4400N/1400W, near the Comstock open cut, unusually coarse conglomerates with a dark hematite matrix occur in the Middle Owen and similar but finer grained conglomerates may be seen at this horizon just north of Mt. Owen summit.

The *Upper Owen Conglomerate* is subdivided in the Lyell area by the Haulage unconformity. Below this horizon is the Chocolate Sandstone, which lies conformably on the Middle Owen conglomerate. It has basal fine conglomerates that provide a transition from the Middle Owen to the Upper Owen. The sandstone is typically pink, thin-bedded, and quartzose, with local shale bands and hematite-rich beds; it is characterized by "balling-up" of sandstone layers by current disturbances and by closely packed jumbles of thin sandstone tubes lying on bedding planes. These are trace fossils and Professor Caster of the University of Cincinatti has suggested that they may represent the fossil excreta of worm colonies. Other types of trace fossils seen in the lower Upper Owen beds have already been described.

The hematite beds are generally less than 3 feet thick, and occur some 200 feet above the base of the Chocolate Sandstone. They are well exposed on Pioneer Spur, where two 3-foot beds, about 10 feet apart, are interbedded with normal pink sandstone. They show the trace fossils of the pink sandstone, but when examined by hand-lens, can be seen to be composed of discoidal elements averaging about 1 mm in diameter. Professor Caster, on being shown a typical specimen, said that it resembled the Clinton iron ore, which is known to be of organic origin; an assay of a representative sample

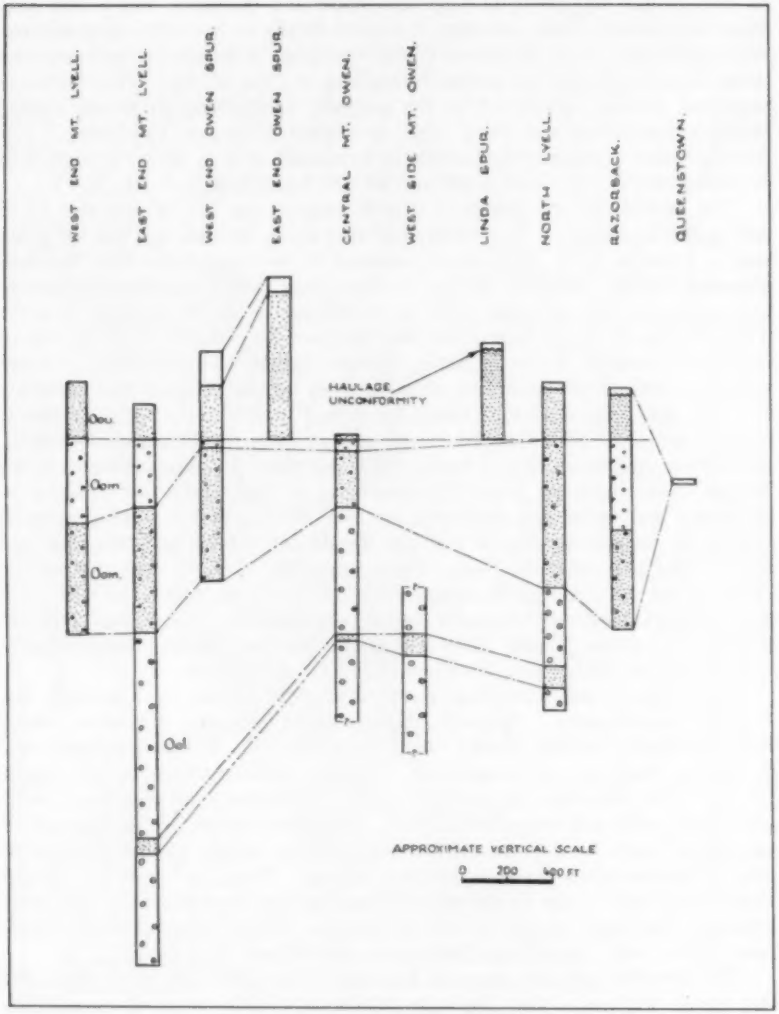


FIG. 9
VERTICAL SUCCESSION IN OWEN CONGLOMERATE IN THE LYELL AREA

indicated 40% Fe_2O_3. In places the hematite bands are associated with gray or yellowish sandstones, as if the iron in the latter had been removed and concentrated in the former. At a number of points, re-crystallization of the iron-rich beds has produced a dense hematitic quartzite. This horizon can be traced from Gormanston to North Lyell and can be seen at Comstock, but on Mts. Lyell and Owen its place is taken by a variable series of hematitic shaly sandstones and thinly bedded quartzites.

The Haulage unconformity marks an interruption to Owen sedimentation and reflects movements along the Lyell Shear. Older sediments were upturned and tightly folded along narrow N–S zones and the ensuing erosion locally removed much of the Chocolate Sandstone. As a result the succeeding Pioneer beds rest almost on Middle Owen Conglomerate at a number of places. East of these zones of localized movement the Pioneer beds rest on Chocolate Sandstone with conformity.

The Pioneer beds rest on the erosional surface cut in Chocolate Sandstone. This is generally overlain by rose-pink conglomerate, gray sandstone, or basal breccia which is well exposed at 700S/00E, near North Lyell, and contains sub-angular fragments of hematite up to several inches in diameter, and pebbles of Chocolate Sandstone. The conglomerate and gray sandstone are characteristic beds that generally contain tiny chromite [1] grains, averaging ½ mm diameter and showing both rounded and sub-angular form. The chromite may well be derived from a serpentine mass newly exposed by the Haulage uplift, though there is no known serpentine in the locality.

Gordon Limestone.—The youngest of the Paleozoic rocks outcropping in the mine area is the Gordon Limestone. It is represented by blue-black shales and clay with local limestone lenses, and has been mapped mainly along the eastern side of the Lyell-Owen divide and east of the Crown Lyell quarry; it is well exposed in the creek beds near Linda. The red clays, commonly carrying native copper, that occur in the synclinal valleys adjacent to the Pioneer, Linda, and Gormanston Spurs are probably derived from Gordon Limestone by hydrothermal alteration.

Pleistocene.—The Pleistocene is represented by glacial moraines consisting of coarse boulders and finer pebbles in a varved glacial clay. This glacial till blankets bed-rock near the Mt. Lyell Mine and Gormanston, and near Comstock. It consists of varved clays and boulder beds and occurs between 850 and 1,500 feet above datum.[2] At its limits it is only a few feet thick but near Gormanston there may be over 100 feet at any one point. The significance of the deposits has already been explained; they mark the limit of a distributary ice flow of the King Glacier, and the site of an ice-dammed lake that overflowed at the Gormanston Gap. The ice did not continue beyond the Lyell-Owen divide, as evidenced by the complete lack of glacial deposits or physical features on the western flank of the range in this area. Again at Comstock the ice sheet did not extend very far west of the western end of Comstock Valley. A few hundred yards west of the Comstock Mines, glacial dolerite boulders occur at approximately 1,700 feet above sea-level,

[1] An analysis of the separated grains gave 56.1% Cr_2O_3.
[2] 100 feet below mean sea level at Strahan.

suggesting that the Comstock ice was thicker than that in the Linda Valley and extended west of the Comstock Mine. Radiocarbon analysis of a specimen of wood in the Gormanston moraine indicates an age of 26,480 ± 800 years, placing the glaciation in the Wisconsin stage (13).

Structure

The Lyell ores occur in rocks that exhibit considerable original lithological differences and variation in mode of formation, and reflect a high degree of Lower Palaeozoic tectonic instability. Minor localized movements culminated

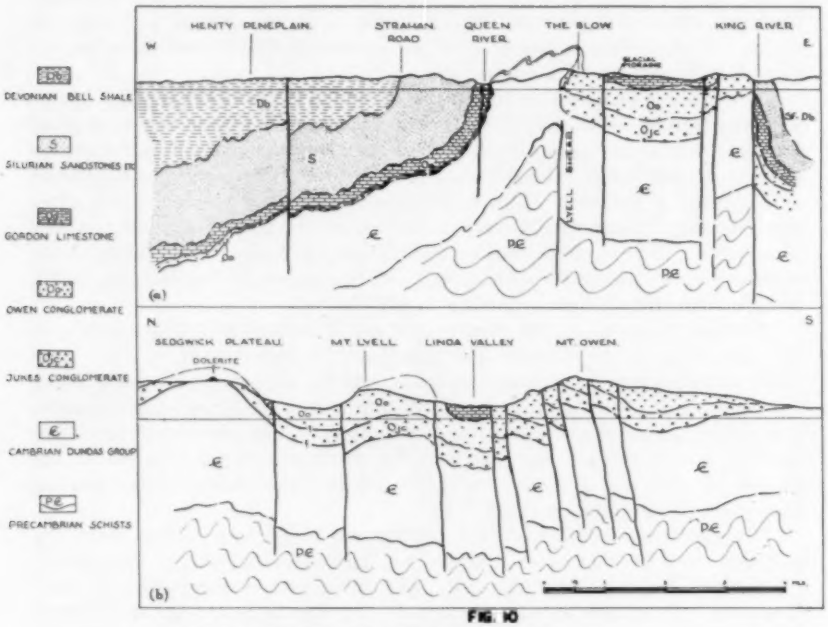


FIG. 10

SECTIONS THROUGH THE LYELL AREA :-
(a) E-W SECTION ON INTERNATIONAL GRID 8200 S.
(b) N-S SECTION FROM MT. SEDGWICK TO MT. OWEN.

in the Devonian Tabberabberan Orogeny, during which the rocks were thrown into their present attitudes.

Earlier movement phases appear to have been localized along the Lyell Shear, a major structure that has been the controlling factor in West Coast Range sedimentation, the movements generally resulting in west-side-up displacements. Commonly, however, the faulting was not simple movement on north-south axes but was accompanied by displacement along east-west lines and was expressed by folding rather than faulting.

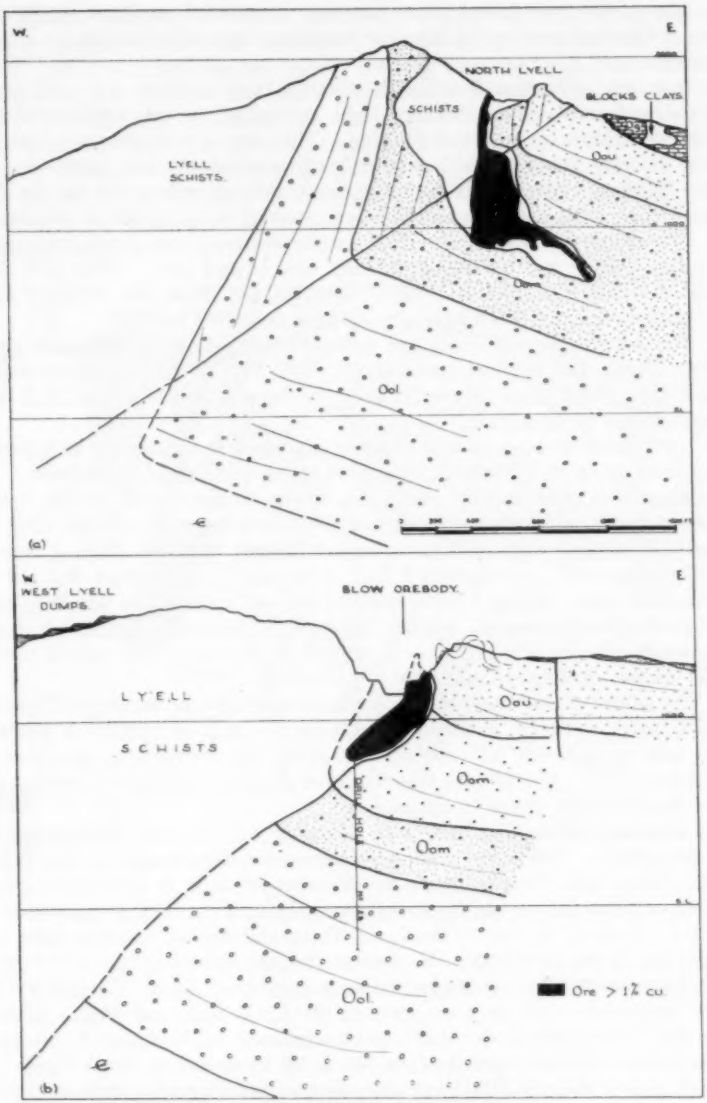


FIG. 11 E-W SECTIONS LOOKING NORTH:
(a) ALONG 200 S. THROUGH THE NORTH LYELL MINE.
(b) ALONG 5600 S. THROUGH THE BLOW

The earliest movement phase that can be studied in detail in the Lyell area is that indicated by the Haulage unconformity and known as the Haulage Movement.

It seems fairly clear that Haulage activity was confined to a zone west of 1100E and consisted of localized tight crumpling on restricted north-south lines, probably as a result of faulting. This was accompanied by restricted E–W faulting, some of which was probably transcurrent and north side west. The Haulage unconformity indicates west side up movement on the Lyell Shear during the early Ordovician, accompanied by east-west displacements.

Tabberabberan Structure.—The conglomerates of the Lyell area exhibit complex folding and faulting on several well-defined lines. The chief structural elements identified by detailed mapping are those also revealed in the regional survey and which have already been described briefly.

The dominating influences are west-side-north and up movement on the Lyell Shear, and vertical transcurrent NW–WNW faulting controlled by the Linda Disturbance; these features are superimposed on the N–S West Coast Range anticlinorium.

Lyell Shear displacement at depth is expressed at the surface as upturning and overfolding on N–S lines, echeloned along the Lyell-Owen divide. The resulting structures may be studied in Owen Conglomerate at the western ends of the spurs that finger out towards Linda from the divide (Fig. 7). The NW striking folds of these spurs are sharply upturned to N–S trend at their western ends, the upturned limb is commonly overturned and exhibits tight, small scale folding. Such features are well exposed on the Whaleback and in the Blow open-cut; surface exposures in the latter locality show only uniformly west-dipping beds, but in section on the south-east wall of the cut, tight isoclinal folding is discernible.

The nature of the Shear movement is indicated by the section in Figure 10 and in more detail by Figures 11 and 12; the axis of upturning generally dips west at between 30° and 50°. Conolly (6) terms this structure the Razorback fold. It is noticed that the point of upturn generally coincides with the thinning of the Owen Conglomerate.

Some difficulty is experienced in following out the axis of the upturning on the surface. It is clear to see at many points, particularly on the Whaleback, Linda, and Pioneer Spurs but in other areas it is apparently absent, and no continuous line can be traced along the divide. This picture of intermittent upturn is typical of the Lyell Shear and similar features have been mapped on a regional scale. It appears that the line of upturn is interfered with by east-west to north-west striking structures (generally faults) that were active either at the same time as the Lyell Shear or slightly after it. Conolly (6) considered the two elements combined and could not be separated in time; he linked the upturn at the Mt. Lyell Mine and at North Lyell by a straight line striking N20°W, and described intersecting folds striking N20°W and N60°W. Actually the upturn strikes longitudinally but outcrops intermittently and *en echelon*, stepping north side west.

The general picture is obscured near the Mt. Lyell Mine by the Razorback fault—this slices across the upturn (Fig. 8) and repeats the structure as shown

by the section in Figure 12. Other faults of near longitudinal trend complicate the upturning and overfolding associated with Lyell Shear movement.

NW and WNW faulting and folding combine with the Lyell Shear to form the basis of the structure at Lyell. As already described in the regional picture, NW-striking high-angle reverse faults form a crude rift structure centered on the Linda Valley, as a result of the influence of the cross-cutting Linda disturbance. With east-pitching folds at Lyell and west-pitching folds at the eastern end of the Linda valley a small basin is formed which Hills (18) described as the "Linda saucer." The two sections in Figure 10 demonstrate the general form of this structure.

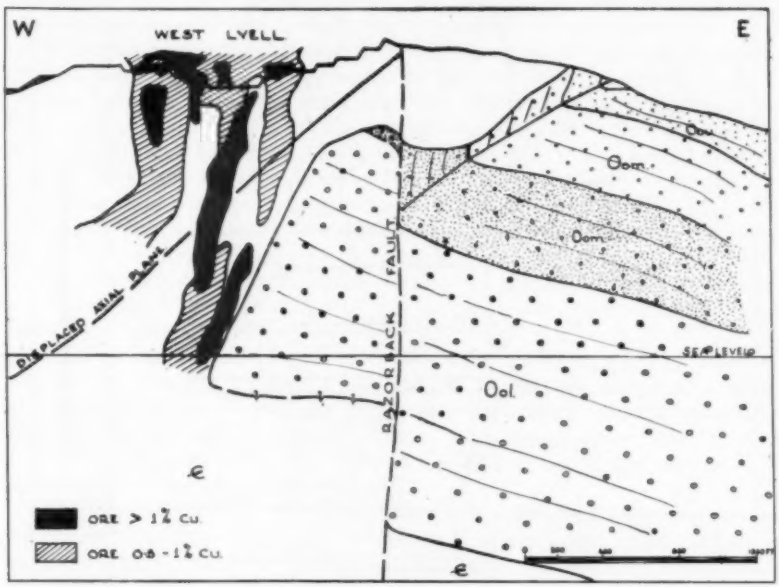
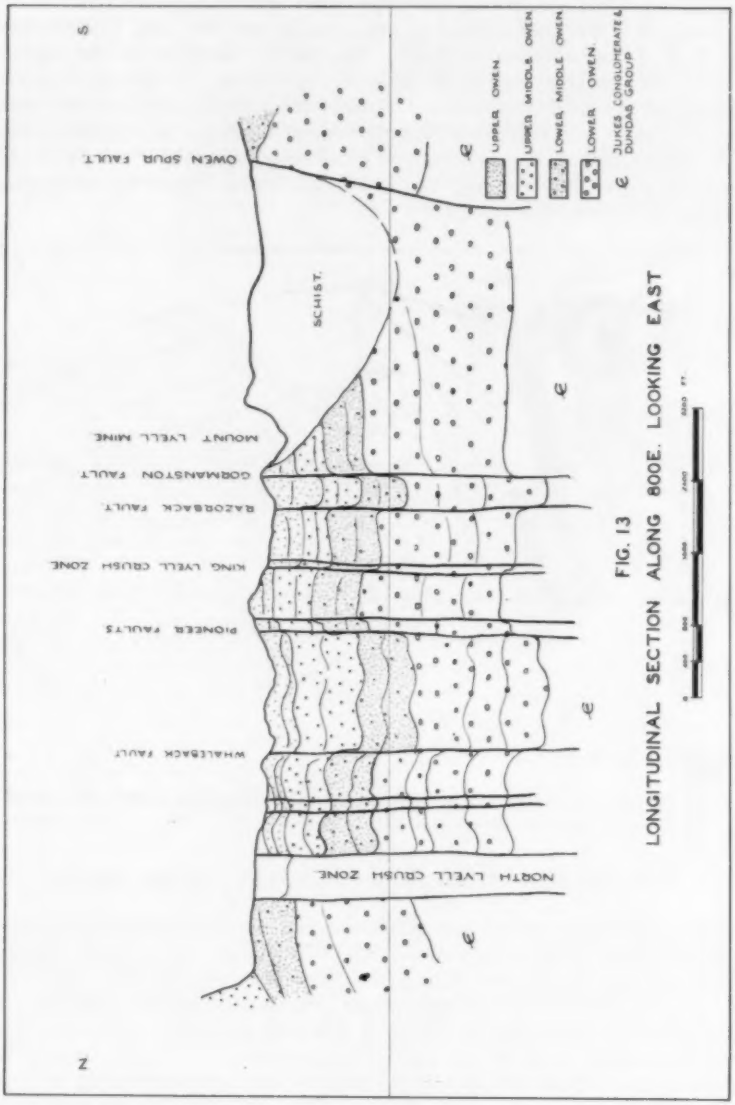


FIG. 12

E-W SECTION THROUGH WEST LYELL ALONG 3600 S.

The Lyell-Owen divide lies on the western rim of this basin and shows north and south facing asymmetrical folds that plunge east. These folds are well exposed on the Pioneer, Linda, and Gormanston Spurs, the ridges coinciding with anticlines and the intervening valleys marking the synclines. In this area they trend almost E–W, with relatively flat south limbs and steep, generally faulted, north limbs; together they impart a wave-like form to the conglomerates. These north-facing folds are met by south-facing features along 2000S, making the zone between 2000S (the Whaleback fault) and 3200S (the Pioneer fault) the lowest point of the rift structure along the divide (Fig. 13). Passing north and south from this area, the conglomerate


S
N
UPPER OWEN
UPPER MIDDLE OWEN
LOWER MIDDLE OWEN
LOWER OWEN
JUKES CONGLOMERATE & DUNDAS GROUP
OWEN SPUR FAULT
SCHIST
MOUNT LYELL MINE
GORMANSTON FAULT
RAZORBACK FAULT
KING LYELL CRUSH ZONE
PIONEER FAULTS
WHALEBACK FAULT
NORTH LYELL CRUSH ZONE
FIG. 13
LONGITUDINAL SECTION ALONG 800E. LOOKING EAST

is gradually stepped up by folding and minor E–W faulting until the Owen Spur and North Lyell faults are reached. These are major faults facing each other across the Linda Valley and marking zones of considerable crushing and vertical throw. North and south of these again the structure is repeated with faults on Mt. Owen throwing down to the north and faults in the Comstock Valley throwing down to the south.

The points of intersection of these NW and E–W faults with the Razorback fold are foci for ore deposition. It is clear from Figure 8 that the location of the major orebodies is closely related to these faults and also to the line of the Lyell Shear upturn and it may be concluded that the local brecciation and crumpling caused by the intersection of these two structural elements has produced suitable host rock for ore deposition.

It has already been suggested that it is uncertain whether the N–S and E–W structures are contemporaneous or not, but in a few cases it seems obvious that the transverse structures have sliced across and displaced the line of longitudinal upturn. This is particularly marked in the case of the North Lyell fault, which offsets the Shear some 3500 feet to the west on its northern side, the axis of upturn at North Lyell is displaced to the west of Cape Horn and then swings back to Comstock in a gentle curve (Fig. 6). The lateral displacement can be explained by vertical movement only according to Conolly (6), but in a similar case at South Owen, a few miles to the south, wrench movement has undoubtedly taken place and it seems probable that the North Lyell displacement is of similar type. As can be seen from the section in Figure 13 the fault also shows considerable vertical throw and the problem is whether the two types of movement took place in one stage of oblique slip, breaking across the Lyell Shear; or whether there was a phase of vertical movement during the NW and N–S folding, followed by a later phase of sinistral wrench movement after Lyell Shear upturning. Similar remarks apply to several of the E–W faults that appear to displace the N–S upturning in a direction north-side-west.

The North Lyell and Owen Spur faults are marked by wide zones of intense crumpling and brecciation where they intersect the Shear, and it is significant that the two richest orebodies, North Lyell and the Mt. Lyell Mine, are closely connected with these complementary crush zones.

Comstock is associated with another major transverse fault (the Comstock fault) but the opposite number on Mt. Owen has only minor mineralization along its length.

The north-east tension faults mapped elsewhere in the Queenstown area have not been found at Lyell. It is possible to link up orebodies on north-east lines, as Conolly has done (6), but as there are no mappable NE structures, this is rather hypothetical. This conclusion is contrary to Bradley's (3b), which assigns considerable importance to NE faults as controlling factors in ore location.

Several lines of evidence suggest faulting has taken place along the contact between schists and conglomerate in a number of places. The movement appears to vary, and involves both horizontal and vertical displacement, resulting in further complications to the structural picture. The contact seen in the

walls of the Mt. Lyell mine open-cut may be cited as an example of contact faulting.

Metamorphic Rocks—Lyell Schists

The Lyell Schists have been the subject of controversy for many years and were included in a discussion of the metamorphism in the Lyell area at a symposium held in November, 1956, at Queenstown. When Gregory made the first detailed examination of the Queenstown area in 1905 (15), he summarized previous opinions on the Lyell Schists. They included suggestions that the schists were altered sediments interbedded with the Owen Conglomerates (21, 23, 25); that they were altered basic igneous rocks (16); and that they were metamorphosed intrusive porphyries of the Dundas Group (33). Gregory considered the schists were originally volcanic ash and intrusive porphyries.

This view was supported by Hills (18) who regarded them as igneous tuffs altered by solutions accompanying ore deposition.

Nye, Blake and Henderson (22) agreed with Twelvetrees (33) in describing the Lyell Schists as an altered complex of igneous rocks intruding the Owen Conglomerate. Edwards (7) and Conolly (6) accepted these views, though Conolly described porphyry sills *replacing* rather than "pushing aside" the conglomerates. Alexander (1) states that replacement of the Owen formation took place "either as the result of an intrusion or by metasomatic replacement."

Hills and Carey (19) and Carey (4) reiterated Hill's earlier views that the Schists were largely altered Dundas Group (Cambrian) graywackes, volcanics, etc.

Bradley (3a, b) repeats Conolly's views that the Schists are largely replaced Owen Conglomerate, though Bradley speaks of granitization and metasomatism rather than intrusion. The authors find truth in most of the earlier opinions for they regard the main mass of Lyell Schists as due to hydrothermal alteration of Cambrian volcanics and sediments, but near the contact, schists originate by alteration of Jukes Conglomerate and Owen Conglomerate.

The Lyell Schists are a series of quartzose sericitic and chloritic schists, strongly developed at Lyell but also occurring at several places along the Lyell Shear where mineralization is intense. They are not necessarily typically developed where mineralization occurs (e.g. at Lake Jukes, where the host rock is a dense blocky felsite).

At most localities they are obviously derived from Dundas Group beds but at Lyell they appear to "intrude" Owen Conglomerate. The schist-sediment contact is intricate and led Conolly to suggest it was an intrusive one.

The schists gradually change in character to the west and pass into unaltered porphyries and sediments of the Dundas Group occupying less elevated regions west of the West Coast Range.

Nature of the Lyell Schists.—The Schists are extremely variable in nature but may be divided roughly into three groups: Quartz-sericite schists; Quartz-chlorite schists; Quartz-sericite-chlorite schists.

The *quartz-sericite schists* are typically developed in the north-western part of the West Lyell open cut. They are gray or yellowish in color but are locally pink due to the presence of very fine hematite, and are essentially coarsely microcrystalline aggregates of quartz with short sericite (?) fibers. An analysis of rather hematitic material is given in Table 2, the high Na_2O content indicating that the sericite is in all probability a mixture of sericite and paragonite. Sericite schists are most common adjacent to the contact and form a quartz sericite zone (Fig. 14) that may be roughly outlined in the field. Their distribution is also closely related to pyrite.

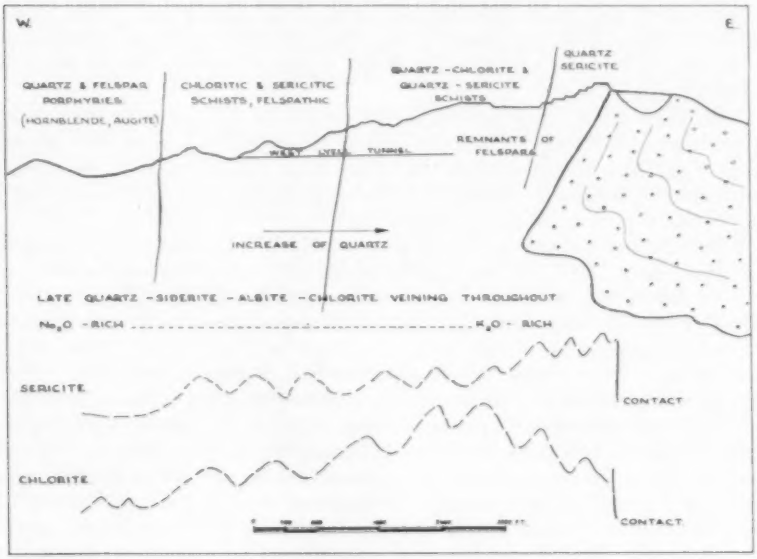


FIG. 14

DISTRIBUTION OF SCHIST TYPES ACROSS THE LYELL - OWEN DIVIDE

The *quartz-chlorite schists* are dark gray-green and are composed of quartz aggregates, chlorite wisps, and generally a fair proportion of Na- or K-mica. The chlorite is generally pleochroic and shows anomalous interference figures typical of pennine. An analysis of typical chlorite schist from the West Lyell open cut is given in Table 2; it differs from the sericite schist mainly in a lower silica content and increased iron, alumina, and magnesia percentage.

An interesting variety of chlorite schist occurs in beds, several feet in width, south of the West Lyell open cut. The rock is a very fine green mass of chlorite and micas, sparsely studded with quartz grains and aggregates less than $\frac{2}{3}$ mm in diameter, and lath-like outlines of sericitic material may represent altered felspars. These chloritic zones alternate with quartz sericite schists that show pronounced banding akin to stratification. This parallels

the margin of the chlorite zones and suggests they may have been basaltic tuffs or basic lavas; however, there is also the possibility that they are basic dikes.

The chlorite of the chloritic schists is probably derived partly from breakdown of ferromagnesian minerals and partly from introduction or re-circulation of magnesium, iron, etc.

Many of the intermediate *quartz-sericite-chlorite schist* types are grayish-green in color and chloritic, but contain a fair percentage of micaceous minerals. A typical type is known locally as sericite-fleck schist; it is gray or dark gray in color and on schistose faces show lath-shaped sericitic flecks aligned with long axes down the dip of the schistosity plane. Thin section show that these flecks are altered feldspars and probably of albitic composition. Less altered felspars are common in the marginal schists near to unaltered Dundas group rocks.

All these schist types are host rocks for ore, though generally the sericitic types are more strongly developed within the orebodies. As a very general rule, it can be said that sericitic schists are more common near to the contact, with chloritic schists increasing in importance outside the sericite zone; this is expressed diagrammatically in Figure 14.

Sericite and chlorite are the chief products of hydrothermal alteration in the ore zone at Lyell. There is little or no argillic alteration within this zone.

An interesting feature of the schists associated with the rich orebodies of North Lyell, the Blow, and Comstock is the development of a variable series of hydrated aluminum silicates with or without Na_2O and K_2O. These aluminum silicates have been variously described as delessite, fuchsite, batchelorite, pyrophyllite, damourite and margarodite, and they have not yet been thoroughly examined and identified.[1] However, they appear to be a series of hydromicas with the essential constituents as silica, alumina, and water. They are typically soft and geasy, greenish in color, and sub-translucent, and they commonly form in zones flanking sulphide lenses. Typical analyses are given in Table 2 (X and XI). These schists appear to represent the highest phase of rock alteration at Lyell. Similar soft pale-green material is often seen in small quantity in the schists away from the contact and it appears to be typical of these hydrothermally altered rocks.

The Lyell Schists, particularly on weathered faces, commonly reveal sedimentary textures—pebble outlines, or stratification, and locally it is possible to trace individual beds. This has been done south of the West Lyell open cut and has revealed evidence on the attitude of the Cambrian rocks. Many of the schists show textures similar to graywacke breccia-conglomerates and may well be representatives of the Jukes Conglomerate. An important feature is that commonly the Owen Conglomerate beds pass along strike to schist of varying types, and this has led to the development of the theories that the schists are sheared intrusives or replacement products of the sediments.

The Lyell Schists of the mine area possess a pronounced cleavage or schistosity that varies in strike from N300E to N330°E and dips steeply to the

[1] Recent research by the C.S.I.R.O., Melbourne indicates variation from pyrophyllite to sericite along with some chlorite.

south-west; the planes of schistosity almost invariably show a lineation down the dip. Between Cape Horn and Comstock, the schistosity parallels the conglomerate, and at Comstock it strikes between N45°E and N60°E. In the West Lyell open cut it is possible to trace a number of other important fractures, joints, etc., chief of which are faults striking about N285°E and dipping flatly to the north. The schists are highly deformed rocks and the vertical lineation probably suggests horizontal movement along the plane of schistosity.

The Schist-Conglomerate Contact.—This contact has been mapped in detail, both on the surface and in underground workings. It is locally irregular and intricate and it is not surprising that many earlier geologists regarded the schists as intrusive. Conolly, however, found such continuity of structures across his so-called sills and dikes that he was forced to regard the schists as replacements of the conglomerates. Similar evidence has forced the authors to regard part of the Lyell Schists as derived from the quartzose Owen beds, but paleogeographic evidence suggests that facies changes account for some of the apparent intrusions and replacements of schist. Thus, at South Darwin there is evidence to show that during Owen Conglomerate deposition, islands of Dundas rocks along the Shear Zone remained elevated and shed graywacke type detritus around their margins. These islands were slowly buried, with the Owen beds gradually overstepping the graywacke detritus until they rested on original Dundas surface. Figure 15 is a diagrammatic sketch of the South Darwin peak area and also shows the result of upturning such a feature.

That similar conditions of sedimentation existed in the Lyell area seems probable as it lies on the Shear and is known as a zone of instability; it is also apparent that the Owen Conglomerate must thin from east to west, for although at Linda the formation is several thousand feet thick, in the Queen River Valley it is less than 20 feet thick.

The similarity between the lower part of Figure 15 and the conglomerate contact at Lyell shown in Figure 11 suggests that the above explanation of the thinning of the Owen Conglomerates is a probable one. It also explains why the conglomerates appear to pass directly along strike into schists, the latter representing the incompetent sheared Jukes formation or beds of the Dundas Group.

It is also possible to explain in a general manner Conolly's "silling" of schist at North Lyell, shown in Figure 11 (a); localized and sudden uplift along the Lyell Shear during Owen deposition might well have resulted in a limited incursion of Dundas detritus in place of siliceous conglomerate, the softer material later being sheared to give the impression of an intrusion of schist.

Thus, the main features of the conglomerate-schist junction may be explained by facies variations along strike and this alone represents a major breakaway from Conolly's idea of intrusion, and Bradley's theory of wholesale metasomatic replacement of the Owen Conglomerate beds.

However, when the contact is examined in detail, several anomalies appear that can be satisfactorily explained only by assuming some chemical alteration

of the Owen Conglomerate. The more important lines of evidence leading to this conclusion are as follows:

At many points along the contact there is an insensible gradation from sandstone and/or conglomerate through sheared material to schist, and the exposures leave a distinct impression that the sediment is being converted to schist.

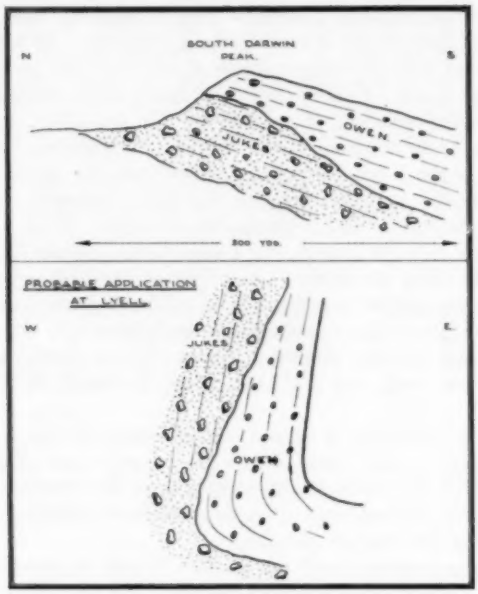


FIG. 13
PROBABLE EXPLANATION OF SCHIST CONGLOMERATE CONTACT AT LYELL

On the Tharsis Ridge (Fig. 8), a prominent E–W fault shows a horizontal slip of almost 200 feet in the Owen sediments, yet the contact of schist and conglomerate on either side of the Ridge shows no displacement whatever. The only reasonable explanation for this feature is that the conglomerates have been partly replaced at some stage after faulting took place. Again, at the southern end of the Tharsis Ridge, the Consols fault coincides with a breakthrough across the strike of the conglomerates that is unlikely to be related entirely to facies changes.

Particularly near the King Lyell clay workings, the sandstones immediately underlying the hydrothermally altered Gordon shales are kaolinized or converted to quartz sericite schists; this is another feature suggesting hydrothermal alteration of siliceous material.

The extent to which the Owen Conglomerate has been transformed is uncertain but it is undoubtedly restricted. Possibly the schisting is confined to a narrow contact zone where high stress conditions prevail due to frictional drag between incompetent and competent materials.

At the recent symposium on the Lyell Schists, many objections, on chemical grounds, were raised against the suggestion that the Owen beds had been altered, yet transformation of quartz to sericite is mentioned by Schwartz (29), and Leedal (20) describes replacement of quartz by albite in the Cluanie igneous intrusion. Again, felspathization of sandstones has been described from many parts of the world.

In summary, the writers believe that field studies show that the majority of the Lyell Schists are sheared and hydrothermally altered facies of the Dundas Group and the Jukes Conglomerate, but that locally at the schist-conglomerate contact there has been some alteration of the Owen formation.

During the course of investigating the nature and origin of the Lyell Schists, other possible solutions were considered. Principal among these were suggestions that the schists were sheared intrusives and also that the intricacies of the contact could be explained by "tectonic intrusion" of the incompetent schists into the massive Conglomerate.

The continuity of structure across schist zones, the lack of "doming," the "space" problem, the prevalence of sedimentary structures within the schist, and their complex nature are major arguments against the existence of a large intrusive mass. Some of the schists may originally have been Cambrian intrusives but if so they were of small extent.

The squeezing of incompetent Dundas rocks into the Owen sequence has undoubtedly taken place and is another factor that has to be taken into account when examining the contact, but all the contact features cannot be explained on this basis and other factors have to be considered.

Marginal Schists.—Passing west from the main area of mineralization, the Lyell Schists become more susceptible to erosion and merge to the typical Dundas rocks exposed in the East Queen River.[3] These marginal schists are less quartzose than those around the mines, are just as variable but generally richer in chlorite, and commonly show felspar (mainly albite) crystals undergoing sericitization (?), chloritization, or carbonation. This propylitic alteration is typical of zones of low-grade mineralization and is observed wherever sulphides occur in this district.

Another feature of the marginal alteration is kaolinization. Near the Smelters the Dundas rocks are converted to a clay, stained red by breakdown of ferromagnesian minerals, and near the Queenstown hospital, quartz-felspar porphyry is kaolinized to a white clay studded with quartz "grains." The zone of kaolinization is most irregular and is outside the zone of propylitization.

Distribution of Schist Types.—The distribution of the schists is indicated in Figures 8 and 14. Quartz sericite schists prevail near the conglomerate contact and in pyritic zones, and are flanked by predominantly chloritic schists.

[3] There is thus an intermediate or marginal zone of schists between the ore zone and the unaltered material of the Dundas Group; it extends along the lower western flank of the Lyell-Owen divide and around to Gormanston.

Anomalies are common and the zones are vague and irregular. Where the pyrite content is greater than 10 percent, then the host rocks are almost invariably sericitic, but copper mineralization occurs in both sericitic and chloritic schists.

Flanking the true Lyell Schists containing sulphides are the marginal schists and these merge outward from the ore zone to unaltered Dundas material.

Zoning such as is represented at Lyell appears to be typical of hydrothermal disseminated copper deposits and particularly the "porphyry" ores (29).

The development of hydrated aluminum silicates (with composition similar to the clay minerals) near to the orebodies, may be the equivalent of the "argillic" zone of alteration described from many ore occurrences.

Mineralogical and Chemical Changes Associated with Hydrothermal Alteration.—A considerable amount of information is available on the chemical composition of the Lyell Schists, but discussion of chemical changes is hampered by difficulties in ascertaining the original nature of particular rock types. It has been shown that the lithologies of the Dundas Group vary rapidly both horizontally and vertically and doubtless the variations of schist types in the mine area are to some extent related to this. The proximity of acid and basic volcanics in the Dundas Group, and of basalts and sandstones, results in wide and rapid variations of chemical composition.

A feature that has to be taken into account at Lyell is the concentration of potash-rich, siliceous volcanics and granite along the Lyell Shear, as already described. If such rocks occurred in the Lyell area prior to mineralization, then schists of similar composition might be expected.

Marginal Schists.—The schists exposed in the first few hundred feet of the West Lyell tunnel are clearly derived from volcanics and graywackes that have undergone alteration involving the formation of chlorite, calcite, sericite and probably paragonite. Felspars of the original soda-rich volcanics may be seen in all stages of alteration to these minerals. Chemically, hydration is ubiquitous, available analyses showing an increase in percentage of combined water of 2–3 percent. Iron also appears to have been introduced, both combined in chlorite and also as fine hematite. Whether there has been transference of other material from outside sources, is impossible to tell from available information, but it is very likely that localized re-distribution has taken place. Schwartz (29a) suggests that much of the material introduced into marginal zones is derived from the mineralized areas.

Lyell Schists.—Quartz-chlorite schists are more intensely chloritized than the marginal schists, are generally more acid with a quartz content, are coarser in grain, and show few relict structures. The few felspar outlines and embayed quartz crystals suggest derivation from volcanics. Chemically, they have a similar combined water content, tend to more acid and have a much lower alkali content with potash and soda in more or less equal amounts. They could well be derived from a volcanic sequence.

Quartz sericite schists are characterized by a high quartz and sericite content. Now if these rocks are derived from original rhyolites or even granites such as typify the Lyell Shear zone farther south, then little chemical altera-

tion is required (Table 2), but if they are derived from the soda-rich, acid and basic volcanics, then considerable introduction of potash and probably silica is required. The lack of granitic and other potash-rich rock pebbles in the Jukes Conglomerate near Lyell suggests that no such material was formed in the mine area. The relationship between high-pyrite content and sericite is so well established that even if the original rocks were in part potash-rich, then considerable movement and re-arrangement of material must have taken place. Original felspars have been almost entirely obliterated or at least reduced to sericitic material and the original quartz has undergone re-crystallization along with silica freed by breakdown of felspars.

Considerable alteration must have taken place to produce the hydrated aluminium silicates of the rich orebodies. Alteration must have involved loss of silica and addition of alumina and water in all varieties, and in some, removal or re-arrangement of alkalies.

Alteration of the Owen Conglomerate formation calls for removal of silica (up to 30%) and introduction of alumina, alkalies, and water.

Hematization.—Much of the schist contact zone is characterized by the presence of hematite, either disseminated in the conglomerates and sandstones near the contact, or as massive lenses at the contact showing relict sedimentary structures. General dissemination is seen near the Blow and massive hematite bodies occur at the northern end of the Tharsis Ridge and near the North Lyell open cut. Detailed mapping has shown that where the Schists occupy the stratigraphical position of the upper Middle Owen Conglomerate, the contact is hematite-rich but where they replace other horizons there is no sign of hematization; for instance, there is no hematite at the contact along the west flank of the Tharsis Ridge, where schists are in the Lower Owen Conglomerate position.

As has already been explained in describing the Owen sediments, the upper Middle Owen beds at Lyell represent a facies variation in that they are poorly sorted and contain angular fragments. Again in the section on the schist-conglomerate contact, the possibility of rejuvenation of the Dundas Ridge at this stage was suggested to explain the schists at this horizon. That the graywacke conglomerates which gave rise to these schists were rich in hematite is very probable, for the unaltered siliceous beds of this horizon are rich in detrital hematite pebbles, presumably derived from the Dundas rocks. It is concluded that the hematite in these beds was expelled during hydrothermal alteration and deposited at or near the conglomerate contact.

Silicification at Lyell.—Silicification is widespread in the Lyell mine area and is particularly associated with major orebodies. Masses of buff-colored chert are developed along the North Lyell fault zone, at North Lyell, and at Comstock, and are a phase of mineralization. Such wholesale introduction of silica into the ore zone is typical of many hydrothermal sulfide deposits and doubtless much of the silica is of deep-seated origin. Possibly also some of the quartz masses result from circulation of pre-existing silica as a result of hydrothermal activity, in the same way as hematite enrichment.

MINERALIZATION

Regional Mineralization

Copper occurrences of varying importance are scattered along the Lyell Shear zone from Comstock to South Darwin (Fig. 5), generally at points of intersection of N–S and E–W or NW structures. The concentration of ore at Lyell is undoubtedly related to the influence of the cross-cutting components of the Linda disturbance.

While the main control is structural, there is also a stratigraphic influence in that the orebodies are located near the same level in the geological column, generally just below the base of the Owen Conglomerate, i.e. in Jukes Conglomerate or Dundas beds. At Lyell, rapid thinning of the Owen sediments, facies changes, and a high degree of shearing result in ore deposition at relatively high levels in the Owen formation.

The controlling factor is not one of geological age but of relative competency, for although the Owen beds are generally impermeable to ore, the competent, easily sheared Dundas rocks allow easy passage for hydrothermal solutions. As a result, the latter tend to become trapped in structural highs immediately below the base of the conglomerates.

The chief copper minerals are chalcopyrite and bornite, with insignificant chalcocite, malachite, and azurite. Pyrite is a common associated mineral, with minor amounts of gold and silver. The host rocks to the copper orebodies include chloritic and sericitic schists (as at Lyell and East Darwin), granophyric felsite (as at Lake Jukes), and hematitic masses (as at Prince Darwin).

Away from the Lyell Shear zone, copper is insignificant and mineralization is confined to minor, irregularly distributed occurrences of gold, barite, galena, stibnite, and zinc blende. Of these, gold was the only mineral present in any quantity but deposits of this metal are now largely worked out. The primary control for this mineralization is again structural and the deposits occur in beds ranging from Cambrian to Devonian in age.

Local Mineralization

The important copper minerals in the Lyell Mine area are chalcopyrite and bornite, with minor quantities of chalcocite, covellite, and native copper, and rarely oxides and carbonates of copper. Pyrite is mined in association with the copper minerals. The principal economic products of the Lyell field are copper, gold, silver, and pyrite.

There is no zone of secondary enrichment at Lyell, though old reports indicate that the Blow was originally capped by a gold-hematite gossan. Incipient supergene alteration and oxidation is seen occasionally near the surface along joints and fracture planes, in the form of carbonates, native copper, tenorite, cuprite, and chalcanthite.

Other minerals associated with those of economic importance have been described by Edwards (7); they are (in approximate order of abundance) hematite, galena, enargite, magnetite, tetrahedrite, tennantite, molybdenite,

electrum, pentlandite, linnaeite, cubanite, and berzelianite (?). The last five have only been recognized under the microscope and by spectrographic analysis. Certain minerals survive flotation and smelting, and are concentrated by electrolytic precipitation in the refinery (see Table 4 for a typical analysis of refinery slimes).

TABLE 4

ELECTROLYTIC REFINERY SLIMES, TYPICAL BULK ASSAY

Copper	76.549%	(by difference)	CaO	0.057
Lead	1.8		Selenium	2.1
Iron	0.11		Tellurium	0.17
Nickel	0.034		Arsenic	0.06
Zinc	Tr.		Antimony	0.13
Cobalt	Tr.		Bismuth	Tr.
Silver	1.62	(508.81 ozs. per ton)	Moisture	7.51
Gold	0.26	(81.005 ozs. per ton)		
Insoluble	1.2			100.000

The copper content of the slimes varies from 72% to 78% approximately.

Edwards and Carlos (9) have published data on the selenium content of the ore minerals at Lyell. The pyritic concentrates yielded selenium percentages between .0038 and .0050 and an average S : Se ratio of 1 : 9,804. The copper concentrates gave .0046% Se and a S : Se ratio of 1 : 8,253. These figures are similar to those given by other hydrothermal sulphide deposits.

The majority of the orebodies are chalcopyrite-pyrite associations, but at North Lyell rich shoots of bornite and chalcopyrite occur with little or no pyrite. Pyrite masses with very little chalcopyrite constitute a third type, and copper clay deposits form a fourth.

The orebodies at Lyell occur in a longitudinal zone about 2,500 ft. wide (Fig 16) extending from Comstock to the Blow. Apart from a section of the North Lyell orebody, the orebodies all occur in the steep limb of the main upturn at Lyell, and location within this limb is controlled by the cross-cutting NW and E–W faults. They are all at or near to the schist-conglomerate contact and occur in schists occupying the stratigraphical position of the Jukes Conglomerate and/or the Dundas Group beds (e.g. West Lyell and the Royal Tharsis) or of the Middle Owen Conglomerate (e.g. North Lyell).

The North Lyell and Blow orebodies occur in the schist close to the conglomerate and their shape conforms to the contact. These orebodies are clearly defined and contain high-grade copper ore, some galena and more silver and gold than elsewhere at Lyell; they contrast with the more irregular, lower grade shoots in schist away from the contact. These lower grade bodies are generally elongated along the prevailing northwest schistosity and dip to the southwest with a pitch of 90° or steep to the north-west. The main examples of this group are the Royal Tharsis, West Lyell No. 1, Prince Lyell, and Crown Lyell orebodies. The Comstock orebodies are parallel to the local trend of the schistosity, which in turn is controlled by the strike of the conglomerate contact.

The ore is almost entirely confined to the schists but here and there in the North Lyell Mine, bornite may be seen in all stages of replacing Owen

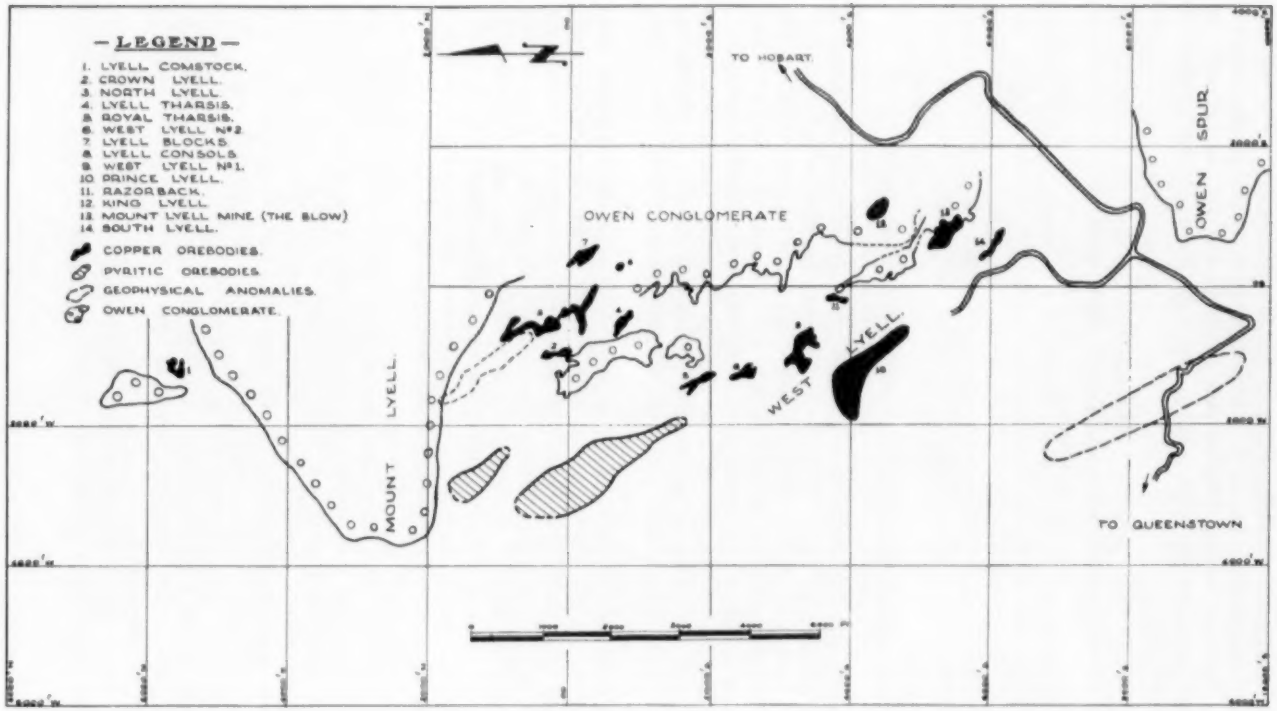


FIG. 16
GENERALISED PLAN OF LYELL OREBODIES.

Conglomerate, with the final stage of solid bornite showing relict pebble outlines on fresh faces. The sulfides in this mine appear to have overstepped the schist-conglomerate boundary.

The gangue is largely unmineralized schist and "quartzite" but quartz veins carrying hematite, siderite, chlorite, sericite, and albite are locally prominent. Barite veins occur at North Lyell and Glen Lyell, and fluorite is rare.

The copper-clay deposits are altered shales of the Gordon Limestone in which native copper has been deposited, possibly as a result of reduction of cuprous hydrothermal solutions by clay minerals. The deposits occur in synclinal basins related to faulting, and in narrow valleys where they are protected from erosion.

The temperature of formation of the ores at Lyell has yet to be investigated in detail. The maximum suggested temperature is 475° C, as indicated by Edwards' (7) discovery of exsolution intergrowths of chalcopyrite and bornite in fragments of copper concentrates. According to Schwartz (28), such intergrowths suggest that the two minerals were heated to at least 475° C, at which temperature they went into solid solution, and then chilled rapidly. However, experiments carried out by A. A. Filimonova (11) indicate that similar intergrowths can form on heating bornite and pyrite together to 240° C, so that Schwartz's figure is open to question.

Other temperature indicators are as follows:

Sphalerite from the Blow is fairly dark brown in color and assays of typical samples average 6.5% Fe. This suggests a temperature of formation lower than the high-temperature deposits like Broken Hill, but higher than typical low-temperature ores (8).

Edwards (7) suggests that some of the chalcocite at Lyell may be of high-temperature type. He describes graphic intergrowths of chalcocite and bornite which Schwartz (27) suggests result from unmixing of solid solutions that form on heating to between 175° and 225° C.

Late-stage gangue minerals (quartz, fluorite etc.) appear to have formed at lower temperatures. Thus, some quartz at West Lyell is smoky, indicating formations below 300° C (2), while fluorite from the same area has retained its typical mauve color, usually lost when heated above 175° C.

Edwards (8) states that siderite is deposited below 250° C but Stringham (31) suggests a range from 500° C downwards.

In summary, the maximum recorded temperature appears to be 475° C and evidence suggests that ore and gangue minerals were introduced with gradually falling temperature to at least as low as 175° C. The entire temperature range is, however, typically hydrothermal.

Ore deposition followed upon the development of the Lyell Schists and metasomatic replacement of Owen Conglomerate. Thus, the orebodies are controlled by schistosity and the form of the contact; at North Lyell the bornite extended its boundaries beyond the schist tongue and replaced the Owen Conglomerate.

Slickensiding of pyrite in the Blow and of ore at North Lyell indicates post-ore movement; also late stage quartz veins distort the schistosity and

locally carry pockets of chalcopyrite picked up from the surrounding schist. The molding of schistosity against the contact may be related to this late stress.

These late-stage veins are very irregular and generally consist of large masses of quartz with limited lateral or vertical extent. Associated with the quartz are minor amounts of dark green chlorite, siderite, albite, chalcopyrite, and pyrite.

THE INDIVIDUAL MINES

Bornite-Chalcopyrite Orebodies

North Lyell Mine.—A small chalcopyrite orebody, known as the Eastern Orebody, was found in 1897, and while building a road to this deposit, rich bornite ore was discovered under a prominent outcrop of hematitic chert. The North Lyell Company raised funds overseas, built a railway to Kelly Basin at the eastern end of Macquarie Harbour (a distance of over 20 miles) and erected a smelter at Crotty, some 10 miles down the Kelly Basin line. However, the siliceous ore was never smelted successfully, and in 1903 the North Lyell Company amalgamated with the Mount Lyell Company. The rich siliceous North Lyell ore blended ideally with the low-grade pyritic Mount Lyell flux for successful smelting.

After amalgamation, the Mount Lyell Company deepened the mine below the existing 500-foot level and found that the orebodies opened out in an amazing manner, reaching a length of 1600 feet at R.L's. 900 and 1000. All told there are some 28 miles of underground drives in the North Lyell Mine.

North Lyell ore averaged 5.4% Cu and the mine produced 200 tons of copper per vertical foot (cf. the Mt. Lyell Mine 120 tons, and West Lyell 700 tons per vertical foot). Between 1903 and 1953 the mine produced 4,642,860 tons of ore assaying 5.4% Cu, 1.12 ozs. Ag per ton, and 0.013 ozs. Au per ton. The mine ceased production in 1953 and published reserves are 3,000 tons of 3.6% Cu ore underground, and 2,500,000 tons of 0.8% ore available for open cutting.

At the outcrop the ore is in a schist corridor, 1,200 feet wide, and about midway between the conglomerate masses of Mount Lyell and the Tharsis Ridge. At depth the ore impinges onto, and at places is actually in, hard conglomerate. The general control is provided by the intersection of the Lyell Shear and the North Lyell Fault, resulting in intense brecciation, silicification, and mineralization.

A notable feature of the North Lyell Mine is the presence of large masses of buff-colored chert veined by hematite.

Mr. Hudspeth, Mine Superintendent for the Mt. Lyell Company, states that the buff chert stopes were entirely chalcopyrite ones. The bornite occurred in three different environments, viz.: (a) Gray quartzite containing appreciable quantities of pyrite and little or no chalcopyrite; (b) White or gray schists with little or no pyrite; (c) In the conglomerate as solid bornite with no visible gangue and no chalcopyrite.

At depth the orebodies lie flatly, controlled by the attitude of the original bedding, but pass vertically up through the fold axis until they become small

vertical pipes in the steeply upturned beds (Fig. 11a). Ore occurs in the upturned and replaced Middle Owen Conglomerates occupying the vertical limb of the Razorback fold immediately south of the North Lyell fault zone.

The ore was mainly bornite in a siliceous gangue, with chalcopyrite, pyrite, galena, hematite, and barite. A typical analysis is given in Table 5. The gold and silver values were below those at the Blow, but higher than in the orebodies away from the schist conglomerate contact. Some of the stopes were phenomenally rich in bornite, having many thousands of tons of ore averaging over 30% Cu. Some of the rich bornite ore has recently been found to be weakly radio-active due to the presence of a small amount of uranium (uranium mineral not determined). The vertical extent of the various ore-shoots was very variable. At depth they merged to form a large irregular orebody and then separated out again in the bottom of the mine.

Chalcopyrite-Pyrite Orebodies

The Mt. Lyell Mine or the Blow.—Gold shed from an ironstone outcrop was discovered at Mount Lyell in 1883 by a party of three prospectors. The party was unable to win sufficient gold to pay its way and other members were admitted, the original prospectors eventually losing their hold on the mine. The Mount Lyell Gold Mining Company N.L. was formed in 1887 and crushing of ore commenced in 1889, but the venture was a failure and the Company went into liquidation in 1891. The Mt. Lyell Mine was first recognized as a copper deposit at this time; Broken Hill investors bought slightly less than a half interest in the mine for £5,000 and in January, 1892, the Mount Lyell Mining Company was formed. Capital to bring the mine to the point of production was provided partly by a bonanza and partly by the sale of shares and £135,000 worth of debentures. Smelters were erected at Queenstown and a steep haulage constructed across Philosophers Ridge to connect the mine with the Smelters; also a 3.5-foot-gauge railway was built from the treatment works to Macquarie Harbour. In 1896 the Mt. Lyell Mine ore was successfully treated by direct pyritic smelting, and in July, 1897, the Company paid its first dividend after absorbing more than £400,000 in development and capital equipment. However, ore reserves and grade were below expectation and within six years, in order to survive, the Mount Lyell Mining Company amalgamated with the North Lyell Company. From 1903, until the mine ceased working in 1929, the Mt. Lyell Mine produced flux ore to blend with the rich siliceous North Lyell ore.

The first one and a half million tons of ore extracted from the Blow averaged 2.85% Cu, 2.67 ozs. of silver, and 0.095 oz. of gold per ton, but the grade declined with depth. After amalgamation with North Lyell in 1903 the ore averaged less than 1% Cu and ore now in reserve in the bottom of the mine averages only 0.5% Cu.

Official production figures are: 1) 1888–89: 1,875 tons of ore yielding 1,670 ozs. of gold, 852 ozs. of silver together worth £6,159. 2) 1896–1929: 5,497,468 tons of ore averaging 1.28% Cu, 2.0 ozs. of silver per ton, and 0.065 oz. of gold per ton.

Ore reserves were last quoted in 1924 as 1,642,122 tons assaying 0.5% Cu, 1.5 ozs. Ag per ton, and 0.04 oz. Au per ton. In the following five years, until the mine closed in 1929, only 17,000 tons of this reserve were mined.

The Blow occupies a similar structural and stratigraphic position to the North Lyell orebodies. The ore occurs in schist occupying the position of the Middle Owen Conglomerate in the vertical limb of the Razorback upturn. The orebody lies between the crushed zones of the Gormanston and Owen Spur faults, the schist penetration along the Owen Spur fault at Gormanston being similar to that at North Lyell. The steep, sharp contact seen on the southern wall of the Blow open cut may well represent a west-dipping fault of the upturned limb. The orebody was roughly elliptical and reached a maximum on No. 4 level where it was 660 feet in length and 270 feet in width; it was worked to a depth of 800 feet. In cross section (Fig. 11b), it was shaped like a banana, the upper richer portion being nearly vertical and the lower, poorer portion lying flatly down the west-dipping asymmetrical synclinal fold axis. There is little doubt that the marked fall-off in grade with depth was related to this change in attitude. The orebody strikes NW and the dip is vertical in the upper part of the orebody but flat to the south west in the lower part.

The ore consisted mainly of pyrite, averaging about 87% FeS_2. Nye et alia (22) reported that chalcopyrite was the most important copper mineral but that enargite, tetrahedrite, bornite, and chalcocite were also present, as well as some galena and sphalerite. Gangue consisted of a little quartz, barite and unreplaced schist; a typical analysis is given in Table 5. Over the ore-

TABLE 5

A typical analysis of Mount Lyell Mine (Blow) ore:

Iron	43.8%	Lead	0.7
Sulfur	50.0	Zinc	0.3
Silica	2.6	Arsenic	0.33
Alumina	0.5	Silver	1.50 ozs. per ton
Barite	0.5	Gold	0.04 oz. per ton
Copper	1.0		

A typical analysis of North Lyell ore in bulk

Copper	6.15%	Barite	1.5
Silica	62.7	Sulfur	Not determined
Iron	9.1	Silver	1.3 ozs. per ton
Alumina	7.5	Gold	0.015 oz. per ton

body, copper values ranged from 0.5% to 6% Cu with a tendency for the higher values to lie on the footwall. Of a number of small rich shoots within the orebody, the most important was the Mt. Lyell bonanza, cut on No. 4 level near the footwall. This shoot yielded 840 tons of ore assaying 21.03% Cu and 1,023 ozs. of silver per ton and produced a profit of £106,312. It consisted of stromeyerite with bornite, chalcopyrite, and gold in a quartz matrix (26).

West Lyell Mine.—The West Lyell group of mines, at one time regarded as too low grade for exploitation, has now become the main producer of copper in the field, containing as much copper as the whole of the rest of the field

combined. The group includes the Royal Tharsis, West Lyell Nos. 1, 2, and 3, and the Prince Lyell orebodies, besides numerous small rich zones. Around all of these orebodies are low grade "halos," which in some cases merge into each other to form a large low-grade disseminated copper deposit capable of being mined in a single open cut, the greatest dimensions of which will be 3,600 feet in length, 1,800 feet in width, and 800 feet in depth. The open cut has been so designed that a total of 105 million tons of material will eventually be removed, 66 million tons of which constitute ore, and 39 million tons waste; the ratio of ore to waste is thus 1:0.58, or a little less than 2:1.

Early attempts to exploit the West Lyell orebodies failed because the grade was too low for underground mining. In 1927 the Mount Lyell Company drilled the Prince Lyell and other lodes, and in 1933 sampled the old Russel Tunnel Workings with favorable results. Open-cutting commenced in 1934 and the operation has been expanded in the ensuing years as diamond drilling has revealed greater tonnages of ore.

GRADE, PRODUCTION AND RESERVES

	Ore	Grade	Waste
Produced	25,471,486 tons	0.72%	13,814,552 tons
Reserve	40,580,000 tons	0.70%	24,862,400 tons
Total	66,051,486 tons		38,676,952 tons
Total Material		104,718,438 tons	

The West Lyell orebodies consist of a series of lenses averaging 1.0 to 1.5% Cu in quartz-sericite schist and quartz-sericite-chlorite schist. Some of the schist is fine-grained, dark, and very chloritic, some is coarsely nodular and rich in quartz and sericite, and all gradations between these extremes occur. Within any single richer oreshoot strips of lower grade ore are strung out along schistosity. Copper occurs mainly as chalcopyrite, with a little covellite and rarely chalcocite; gold and silver values are low but significant.

All of the orebodies, including the top of the Royal Tharsis, are included in the one open cut in which the average grade of ore is 0.7% Cu with the waste varying from approximately 0.1 to 0.3% Cu. The pyrite content at West Lyell averages about 9.5%. The Prince Lyell has proved to be the largest orebody in the field and its downward extension is still not outlined.

Ore control at West Lyell consists of vertical east-west faulting intersecting the Razorback fold, the steeply upturned west limb of which consists of schists. The wide zone of schists at West Lyell must occupy the original position of the Jukes Conglomerate and probably part of the Dundas beds. Deeper drilling is required to locate the base of the Lower Owen at West Lyell.

The strike of individual ore-shoots is slightly oblique to, and the dip is slightly steeper than, schistosity, and each ore-shoot tends to approach closer to the conglomerate contact at depths so far drilled (Fig. 12). The dip is always steep to the south-west and the pitch is variable though always steep. The Royal Tharsis has a 90° pitch, the Prince Lyell 90° or very steep to

the northwest, and the West Lyell No. 1 pitch corkscrews. The smaller orebodies pitch in varying directions.

Smaller chalcopyrite-pyrite orebodies that have made a significant contribution to production at Mount Lyell are the Crown Lyell, the Royal Tharsis, the Lyell Tharsis, and the Lyell Comstock.

Crown Lyell.—The Crown Lyell orebody was relatively small, varying in length from 150 to 290 feet, and in width from 30 to 70 feet though there is a considerable halo of 1 percent copper ore unmined.

Very little ore was produced prior to 1931 but between 1931 and 1955 when the mine closed, 436,000 tons of ore were produced assaying 1.65% Cu, 0.259 oz. Ag per ton and 0.014 oz. Au per ton. The orebody was mined down to No. 6 level, at which level it decreased considerably in size. There is evidence of a new unprospected echelon of ore in the Crown Shaft between the 500-and 700-foot levels.

The Crown ore occurs in schist, replacing the ore horizon of the Middle Owen Conglomerate and is on the steep west limb of the Razorback fold, adjacent to the North Lyell fault zone.

Royal Tharsis.—The Royal Tharsis and South Tharsis mines were worked in separate leases in the early days of the field though they are one and the same orebody. The main production came from the mine after 1930 following the driving of the North Lyell Tunnel nearby in 1927. Ore was mined more or less continuously from 1937 to 1954 when the mine was closed. This was the last of the underground mines to close and marked the end of 63 years of continuous underground work at Mount Lyell.

Total production from this orebody between 1900 and 1954 was 1,578,368 tons, assaying 1.58% Cu, 0.017 oz. Ag, and 0.0002 oz. Au.

The reserves above R.L. 700 feet are given as 954,000 tons of 1.6% Cu.

The Royal Tharsis is a member of the West Lyell group of orebodies that extend *en echelon* to the southwest from the Tharsis Ridge, and are separated by low-grade zones. The Royal Tharsis ore occurs in a sericitic quartz schist with pyrite and chalcopyrite. Of all the West Lyell orebodies it is the closest to conglomerate, being within 100 feet of the conglomerate on the Tharsis Ridge and separated from sediments by schist carrying low copper values. The orebody is elongated along schistosity and reaches a maximum of 550 feet in length and a width of up to 100 feet. A deep diamond drill hole passes from the footwall into conglomerate at sea-level, 750 feet below the deepest workings and 1,800 feet down dip from the outcrop. The grade improves steadily with depth. The orebody dips SW at 65° and has a 90° pitch.

Lyell Tharsis.—This was one of the four early mines to be worked profitably, and from 1899 to 1901, a total of 60,167 tons of siliceous ore was sold averaging 4.64% Cu and containing 36,660 ounces of silver. In the following years its grade declined and open-cutting of a low-grade halo surrounding it commenced.

Total production to 1956 was 759,800 tons of 1.48% Cu ore and the reserves available by open cutting are 800,000 tons of 1% Cu with an overburden of 387,873 tons, a ratio of ore to waste of 2.1 : 1.

The Lyell Tharsis orebody is in an environment similar to that at North

Lyell, except that it is south of the North Lyell fault and is associated with a strong E–W fault. The ore (predominantly chalcopyrite with some bornite and galena) is in schist, separated from conglomerate by a thin strip of hematitic schist and it occurs in the steep upturned west limb of the Razorback fold in the Middle Owen horizon. The schist does not extend far down the steep limb and mineralization cuts out only 400 feet below outcrop. The strike follows NW schistosity and the dip is vertical.

The Comstock Mines.—The Comstock group of orebodies is situated in the Comstock Valley, on the northern side of Mount Lyell, about one mile north of the North Lyell Mine. The early history of the Comstock area from 1901 to 1912 is one of slow exploration and development from adit levels with very little ore production. The Mount Lyell Company purchased the property in 1913 and immediately set about its development. This phase of development, with stoping, continued until 1921, with much of the ore coming from the open cut after 1915. Work was suspended from 1922 to 1929 but from then until 1944, when operations ceased, the mine was steadily deepened and levels were opened down to 1200 feet below outcrop.

The orebodies at Comstock, as at Lyell, occur in Lyell Schists near the contact of schist and conglomerate. They are located on the intersection of the Lyell Shear and the E–W Comstock fault and the degree of brecciation and the grade of ore is second only to that at North Lyell. Like North Lyell, the ore is associated with the development of massive chert bodies veined by hematite.

The Middle Owen Conglomerate passes along strike into schist containing the Comstock orebodies. Four separate orebodies have been located and their arrangement in section is roughly *en echelon,* although individual orebodies connect at certain levels. Edwards (*7*) noted that the upper two orebodies have the shape, in plan, of two opposed "V's" related to the two local cleavage directions, and that both orebodies dip to the north west at 60° and pitch to the south west at 60° and 78°. They attain a maximum length of 270 feet and a maximum width of 70 feet. Of three ore-shoots, the first and second are worked out, the third is only partially mined and on the fourth, which echelons in at depth, mining had scarcely begun when the mine was closed. The first echelon was shallow. The second echelon was mined from surface (R.L. 1650) down to its limit at R.L. 1300; the third echelon persists from outcrop at R.L. 1750 to below No. 11 level (at least) at R.L. 700 and lies to the west of the first orebody; the fourth echelon had its summit at R.L. 1200 and it also persists below No. 11 level.

Ore consists of disseminated chalcopyrite in schist with some bornite in the first and fourth echelons. Pyrite is present and Edwards (*7*) records magnetite, galena, copper carbonate, and free gold. Aluminum phosphate has also been found at Comstock.

The Tasman and Crown Lyell Extended.—This mine lies immediately east of the Lyell Comstock mine and in it two orebodies have been worked to a shallow depth from three levels. The orebodies are approximately 200 feet apart, one containing patchy bornite in schist and brecciated quartzite, and the other a small but rich lode containing lead, zinc, and silver. The

average metal values for the latter ore are given as: Lead: 28.0%; Zinc: 20.0%; Copper: 0.5%; Silver: 16.00 ozs. per ton; Gold: 0.01 oz. per ton.

The Tasman and Crown workings are in schist along the strike of steeply upturned Owen Conglomerate.

The Copper Clays

Copper clay deposits occur in valleys on the eastern slopes of the Lyell-Owen divide. The three main deposits are, from north to south, the Blocks, the Lyell Consols, and the King Lyell Mines (Fig. 16). They are all in shales of the Gordon formation that have been altered by hydrothermal solutions to ferruginous clays carrying native copper.

The deposits are only partially exploited and although a considerable tonnage of material is indicated, no reliable estimate of tonnage and grade is known. Difficulties in mining and treatment have hindered exploitation to date.

At the *Blocks Mine* the clays were first concentrated in 1904 and 15,000 tons of ore had been won by 1907 when the rich workings above tunnel level caved in. The ore appears to have averaged 2–3% Cu.

The *Lyell Consols Mine* was open only for two years, 1909 and 1910, and the orebody then was described as being 400 feet in length and containing over 94,000 tons of 3% Cu ore.

The *King Lyell* clays were worked to a very shallow depth and a thin layer of clay was sluiced on the southern slope of Pioneer Spur. Boreholes show that the ferruginous native copper clays are surrounded either by unaltered black shales and limestone, quartz sericite schist, or kaolinized sandstone. The grade of the clay ore is between 1% and 2% Cu.

Pyrite Orebodies

Several fairly large pyritic lenses occur in the Lyell area; they contain little or no copper and at present are not of economic significance. They have been outlined by electro-magnetic surveys and field mapping, and a number have been drilled. They are similar orebodies to those at West Lyell but contain insufficient copper for exploitation. They are elongated along schistosity and contain large tonnages of ore assaying as high as 80% FeS_2.

The only pyrite orebody that has been mined is the South Lyell orebody. This lies about 800 feet south-west of the Mt. Lyell Mine and was worked in order to assist in smelting the siliceous North Lyell ore and for export to acid works. It was discovered at a depth of approximately 500 feet and stoping continued down about 400 feet; it attained its maximum development of 540 feet in length and 90 feet in width on the No. 8 level of the Mt. Lyell Mine.

The South Lyell Mine produced 325,830 tons of highly pyritic ore and reserves are 294,000 tons of ore high in sulphur. The orebody appears to go to considerable depth.

FUTURE PROSPECTS

A consideration of this paper leads to the question of what happens in depth at Lyell, below the base of the Owen Conglomerates, where optimum conditions for ore deposition might be expected. The answer to this question is not yet known because the position is unexplored; serious diamond drill hole deflection, uncertainty of target depth, extremely slow drilling in hard conglomerate, and pressing demands for shallower drilling have combined to defer prospecting at depth. However, the time is rapidly approaching when deeper drilling will be undertaken. The Mount Lyell copper-bearing zone is virtually unexplored at a depth greater than 1,500 feet below outcrop and structural considerations indicate that considerable new ore reserves could occur below this depth.

ACKNOWLEDGMENTS

The authors are indebted to Mr. G. Hudspeth, Mine Superintendent, and Mr. Alexander, Assistant Mine Superintendent, for a great deal of local information and for constructive criticism during preparation of this paper. Thanks also are due to Professor S. W. Carey, M. Banks, A. S. Spry, and Dr. E. Williams of the Geology Department, University of Tasmania, for helpful advice and criticism.

GEOLOGY DEPARTMENT,
MOUNT LYELL MINING AND RAILWAY CO. LTD.,
QUEENSTOWN, TASMANIA, AUSTRALIA.
Oct. 12, 1957

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Economic Geology
Vol. 53, 1958, pp. 417–425

URANIUM-BEARING AURIFEROUS REEFS AT JACOBINA, BRAZIL

J. D. BATEMAN

ABSTRACT

Near Jacobina, Brazil, are uranium-bearing gold deposits in reef-type conglomerates of Proterozoic age. Uraninite and gold occur in association with pyrite in the matrix of closely packed quartz pebble conglomerates. A comparison of the geological and geochemical features is made with the Witwatersrand gold ores and the Blind River uranium deposits, leading to the conclusion that, in the three widely separated areas, the deposits are the product of a similar metallogenetic cycle of erosion, sedimentation, and mineral deposition restricted to a late Precambrian epoch.

INTRODUCTION

GOLD-BEARING conglomerate reefs in the Serra de Jacobina, State of Bahia, Brazil, have been worked at intervals over many years. Geologists familiar with these deposits have recognized the lithologic and mineralogic analogy with the auriferous bankets of the Rand in South Africa, leading to speculation on the possibility of extensive payability in the Jacobina reefs. Gold mining operations, however, have been conducted on a very small scale and at present, other than small native workings, only the Canavieiras mine is in production, treating some ten tons of ore daily.

Following the initial exploration of the uranium-bearing conglomerates at Blind River, Ontario in 1953, the temptation to compare the similarity of geological features of this area with the Witwatersrand became irresistible; and the analogy of uranium and gold associated with a pyrite-bearing sericitic matrix in reef-type quartz pebble conglomerates was inevitably emphasized by many geologists.

At Jacobina the gold is associated with pyrite and sericite-chlorite in quartz pebble conglomerates. Why not uranium? The only specimen of Canavieiras mine ore available to the writer in Canada was tested with the geiger probe in August, 1953, and found to be significantly radioactive. The specimen yielded 0.103% U_3O_8 by chemical assay. This discovery led to a visit by the writer to Jacobina during May, 1954, to investigate the uranium-bearing gold ores.

In a recent discussion of the origin of uranium in ancient conglomerates by Davidson (3) brief reference is made to the presence of uranium in the Jacobina reefs. As the only account of these occurrences published in English (11) is not widely circulated, it is hoped that the present discussion will provide additional facts to assess the reef-type or banket gold-uranium deposit. Studies of the occurrence of uranium in the ores of both Blind River and the

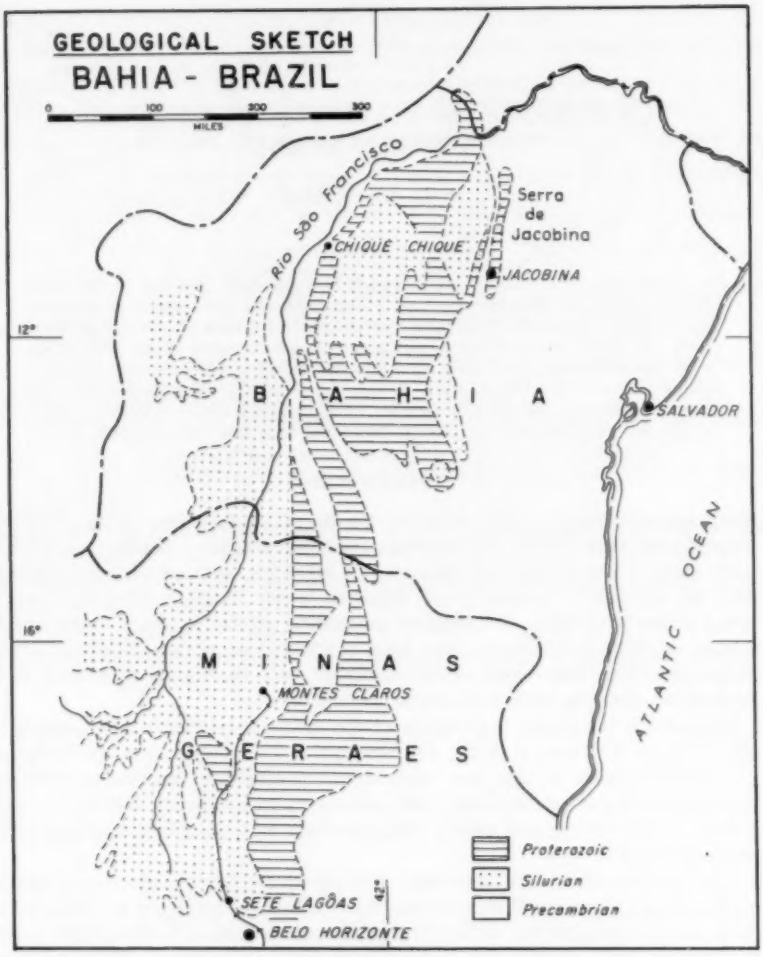

FIG. 1.

Rand have re-opened the almost dormant controversy on the origin of the Rand gold deposits—hydrothermal or placer? Whereas the relatively undeveloped gold-uranium deposits at Jacobina are as yet of little economic significance, the geological evidence they provide should not be ignored in comparative evaluations; and may have some impact in the arena of conflict between the proponents of epigenetic or syngenetic origin of this type of deposit.

GEOLOGICAL SETTING

Jacobina is situated in the State of Bahia, 170 miles northwest of the Atlantic port of Salvador; and is accessible from there by hard-surfaced road. The district is also served by a narrow gauge railway. Jacobina is in the southern part of the Serra de Jacobina, a prominent north-trending range of hills that rises abruptly above the Archean plain of Bahia (Fig. 1). The Serra de Jacobina extends northward as an isolated geological unit for a distance of 140 miles, having an average width of 20 miles, and with a relief above the surrounding plain between 1,800 and 3,000 feet.

The range consists of a sedimentary series completely enclosed by the Archean crystalline basement. The sedimentary formations have been named the Jacobina series (2) and are correlated with the Minas series of Proterozoic age (7), although the Jacobina series is described as being more strongly folded and metamorphosed than typical Minas.

The Jacobina formations consist of thin-bedded to massive quartzite and feldspathic quartzite with extensive conglomerate horizons and lenses in the lower part; and is overlain by argillaceous sediments now largely represented by phyllites. The formations are part of a geosynclinal succession of deposition, and bear many similarities to the Lower Huronian at Blind River and the Upper Witwatersrand system of the Transvaal, the analogy extending to moderate deformation and an indicated early Proterozoic age in each instance.

The entire sedimentary succession at Jacobina dips to the east at an average inclination between 45 and 65 degrees. The structure is thus homoclinal; but as the stratigraphy has never been mapped in detail, and multiple faulting is known to exist, the true thickness of the sedimentary succession is not determined, although it must be measurable in tens of thousands of feet. The basal formations rest unconformably on the Archean crystalline basement along the west side of the belt, and the eastern front of the range is assumed to be terminated by faulting.

GEOLOGY NEAR THE CANAVIEIRAS MINE

In the vicinity of the Canavieiras mine, 4 miles south of the town of Jacobina, Flaherty (5) divides the Jacobina series into a lower Canus group of thin-bedded and cross-bedded quartzites containing a number of conglomerate horizons, and an overlying Serra group of massive quartzites (Fig. 2). The Canus group, which is exposed over a width of one mile with an eastward dip of 55 degrees, rests on Archean granite and granite-gneiss. The gold-bearing reefs of the district are confined to the Canus group and generally lie well above the basal beds. This formation has been recognized over a distance of at least 20 miles and contains innumerable conglomerate horizons.

The sedimentary sequence is cut by sub-concordant ultra-basic dikes altered to a serpentine-talc-chlorite assemblage. One such dike lies in the valley adjacent to the Canavieiras mine and has been subjected to lateritic weathering.

The Jacobina series is transected by a number of steep angle transverse faults having both right and left hand displacements and horizontal offsets up

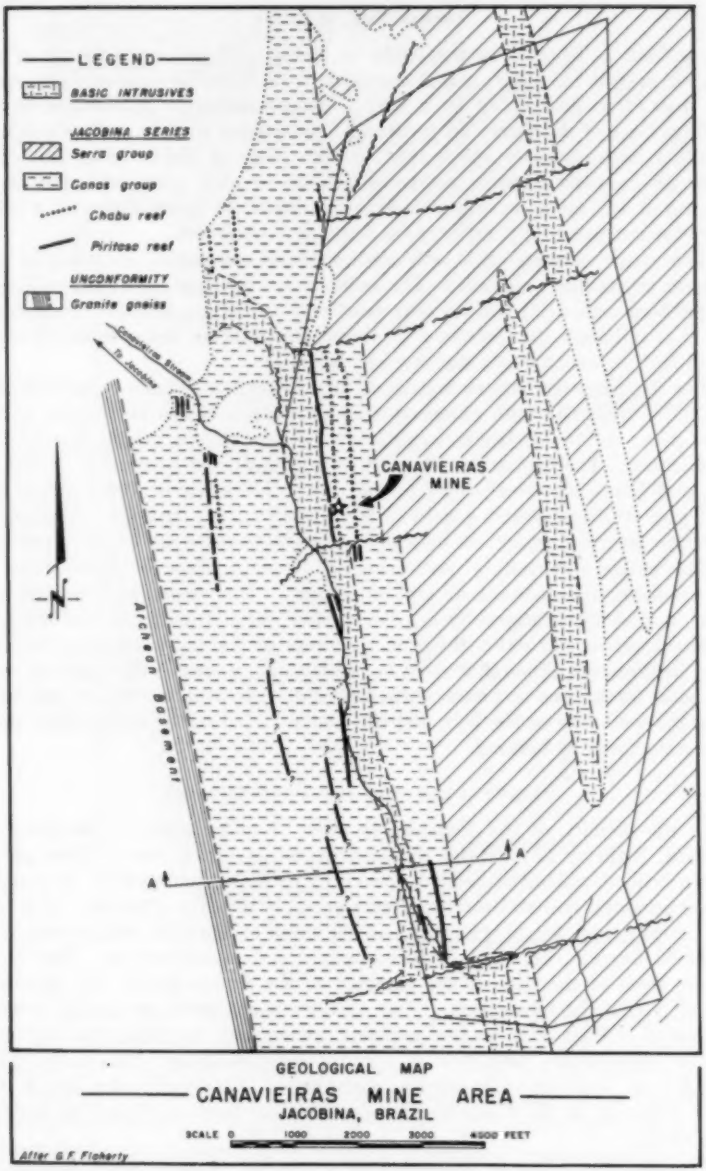
LEGEND
BASIC INTRUSIVES
JACOBINA SERIES
Serra group
Canas group
Chabu reef
Piritoso reef
UNCONFORMITY
Granite gneiss
Canavieiras Stream
To Jacobina
CANAVIEIRAS MINE
Archaean Basement
A
A
GEOLOGICAL MAP
CANAVIEIRAS MINE AREA
JACOBINA, BRAZIL
SCALE 0 1000 2000 3000 4000 FEET
After G.F. Flaherty

FIG. 2.

to 1,200 and more feet. In a number of instances such faults limit the distance a conglomerate reef may be traced along the outcrop.

Two types of conglomerate reefs have been distinguished in the Canus group by Flaherty (5), namely the Piritoso and Chabu-type reefs. The Piritoso reefs consist of glassy quartz pebble conglomerates with a chlorite-sericite matrix mineralized with pyrite. The Chabu reefs are composed of porcellaneous weathering white quartz pebbles and cobbles in an arenaceous matrix. All the significant radioactivity and economic gold deposits of the district are confined to the Piritoso-type (pyrite-bearing) reefs.

Native workings for gold extend along the western front of the Serra de Jacobina in the Canus group for a distance of at least 40 miles. Individual ore-bearing conglomerate horizons cannot be correlated within this distance and, in fact, the lenticular habit of the conglomerate, faulting, and overburden preclude any prospect of correlation.

GEOLOGY OF THE CANAVIEIRAS MINE

The mine is situated on the lower east flank of the steep-sided valley in which the Canavieiras stream flows. At this locality four principal conglomerate reefs are recognized in the upper part of the Canus group, although a complete cross-section of the Canus contains an additional number of reefs (Fig. 3). Flaherty (5) has named the principal reefs in descending order as follows:

Maneiro	(Chabu-type)
Hollandez	(Chabu-type)
Liberino	(Piritoso-type)
Piritoso	(Piritoso-type)

The main mine workings are in the Piritoso reef and extend into the Liberino reef. The reefs are exposed for a distance of 3,000 feet, terminating against a fault to the north and obscured by overburden to the south. The reefs attain a maximum thickness in the order of six to eight feet; but are perceptably lenticular and may thin to a row of pebbles along a bedding plane, or split into two or more members. Gold and significant radioactivity occur in ore shoots within the thicker parts of the reefs.

In the Chabu-type reefs white quartz cobbles are up to six inches in diameter. Little sericite or chlorite is present in the matrix and pyrite, if present at all, is very sparingly disseminated. Low-grade gold ore shoots, as indicated by surface sampling, may occur in the Chabu-type reefs. Radioactivity on the outcrop is very weak, and samples show only trace amounts of uranium.

In the Piritoso-type reefs reddish-pink glassy quartz pebbles, most of which are in the range of 1–1½ inches in diameter, account for 60 percent of the reef. The matrix consists largely of green chlorite and sericite liberally sprinkled with finely divided pyrite. Some pyrite is observed filling fractures in the matrix. Gold-bearing ore shoots and small, but significant, amounts of uranium occur in such reefs, there clearly being a quantitative relationship between the gold, uranium, and pyrite. The quartzite enclosing the reef is

a light greenish color and, in this respect, resembles the quartzite containing the uraniferous conglomerates at Blind River.

Surface Leaching.—Studies by White (10) show minor radioactivity in surface sampling as compared with appreciable radioactivity in samples taken from the mine workings. As an example, surface sampling of the Piritoso reef returned 0.006 percent uranium equivalent as compared to 0.03 percent equivalent in run-of-mine ore. There is no thorium present and the uranium series is in equilibrium.

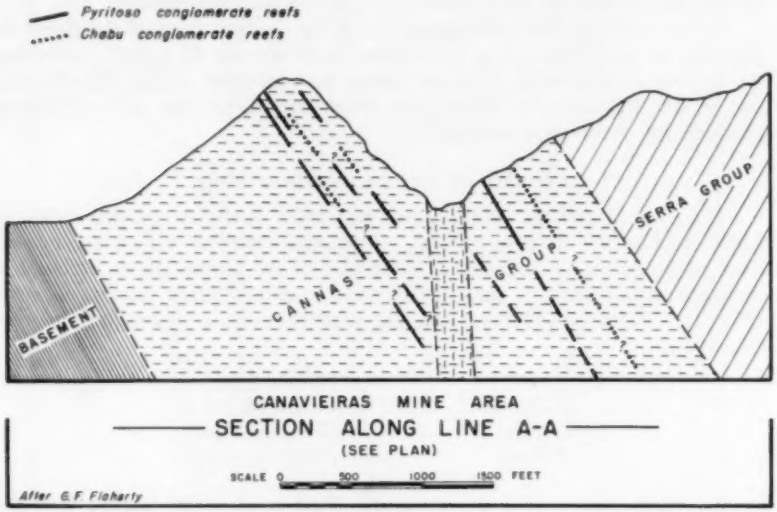

FIG. 3.

Schnellmann (9) observed that the gold content of the ore mined was almost twice that indicated by surface sampling. He concluded that leaching had taken place, and implied the probability of secondary enrichment in the ore shoot. These conclusions applied only to observations on the distribution of gold.

Despite a tropical environment there is little evidence of deep weathering on the steep outcrops of the reefs and, in fact, pyrite is exposed on the weathered surface with only a slight tarnish. In some rock trenches concentrations of loose gold have been found, suggesting that gold freed by weathering has been concentrated in near-surface fractures. While some leaching near the surface is to be expected, the writer was unable to find any evidence suggesting secondary enrichment other than local concentrations of gold in near-surface fractures.

Underground Observations.—Although surface sampling has indicated an ore shoot 850 feet long in the Piritoso reef and 800 feet long in the Liberino reef, the underground excavation is limited to a length of about 450 feet and to an inclined depth of 250 feet. The reef is about five feet thick and is mined

over this width. Within the reef are thin beds of quartzite that are barren of gold and radioactivity. This material is sorted by hand at surface, and the grade of mill feed is approximately one ounce of gold per ton, the average tenor of the reef being about 0.45 oz./ton and 0.015% U_3O_8. The pyrite content ranges from three to five percent.

Although gold is distributed throughout the matrix of the reef from hanging wall to footwall, most of the uranium and pyrite are concentrated over a thickness of one to two feet of the central part of the reef in the mine workings. Within this section the gold content is higher than average, and the uranium content is estimated to be 0.05% U_3O_8. Individual samples may return as much as 0.40% U_3O_8.

Oxidation on a local and minor scale extends to variable depths in the workings, and is recognized by the presence of indigenous limonite. Limonite is most prominently developed adjacent to fault surfaces. Where obvious oxidation has taken place uranium has been extensively leached.

No hydrocarbons have been identified in the ore, and thorium is not present in more than trace amounts. White (10) states that the radioactive mineral is uraninite.

Uranium in Mill Products.—All the mill products are distinctly radioactive, but most of the uranium is separated with the pyrite table concentrate. The blanket discharge was accumulated in a stockpile over several years and, at the time of the writer's visit, was being treated in a cyanide leach plant. Those parts of the stockpile originally high in pyrite, as recognized by concentrations of limonite, were found to be strongly radioactive and weak radioactivity was present throughout the cyanide tailings.

Radiometric assays of some mill products obtained in 1954 are as follows:

Sample No.	Source	β Equiv. $\%U_3O_8$	γ Equiv. $\%U_3O_8$
2051	Amalgam barrel heads	0.23	0.23
2057	Amalgam barrel heads	0.205	0.20
2048	Table concentrate	0.039	—
2047	Amalgam barrel tails	0.018	—
2053	Amalgam tailings pond	0.016	—

The amalgam barrel heads are essentially a pyrite concentrate, and further confirm the association of uranium with pyrite and gold.

GEOLOGICAL CONSIDERATIONS

On the Witwatersrand it is generally conceded (4) that the reef-bearing sedimentary formations were deposited on a broad surface close to sea-level, although various studies have placed emphasis on a lacustrine, marine beach, delta, terrestrial, and even glacial origin. Scour and fill, cross-bedding, and braided channels are recognized associated with the reefs.

McDowell, following a study of the lowermost Huronian at Blind River (6), favors a fluvial origin for the lower formations containing the uranium-bearing reefs, followed by marine or lacustrine submergence for deposition of the overlying siltstones and argillites. On the Rand and at Blind River the trends of ore shoots are related to the trends of the primary sedimentary structures, and at Blind River there is a suggestion that the ore conforms to

depressions in the basement (8). Both on the Rand and at Blind River mine geologists recognize the relationship of ore to the sedimentary petrology and structure, and utilize this condition in the search for ore. A similar stratigraphic control of ore applies at Jacobina. These relationships, however, are not *prima facie* evidence of ore deposition contemporaneous with sedimentation, for the primary sedimentary features could equally as well have controlled circulation of solutions and consequent deposition of the ore minerals.

At Jacobina the primary sedimentary features are largely consistent with those on the Rand and at Blind River, although the lenticular structures of the reefs and braided channels are more pronounced, and an alluvial origin is indicated. Ore-bearing reefs at Blind River may occur at the base of the Huronian and generally are within 200 feet of the basement. At Jacobina the gold-bearing reefs are 1,800 to 3,000 feet above the base of the section; and on the Rand auriferous reefs extend through several thousands of feet, the most productive reefs being well above the base. Some comparative features of the ore from the three districts are tabulated below:

	Witwatersrand	Blind River	Jacobina
Gold (oz./ton)	0.2–0.8	trace to erratic highs	0.25–0.45
Uranium (% U_3O_8)	0.01–0.06	0.09–0.13	0.02–0.04
Thorium (% ThO_2)	Trace	0.05	Trace
Pyrite (%)	2–10 (fine-grained)	5–12 (coarse-grained)	2–5 (fine-grained)
Pebbles	Glassy quartz	Glassy quartz	Glassy quartz (pink)
Pebble diameter (av. inch)	1	1¼–1¾	1–1½
Pebble-matrix ratio	70:30	65:35–40:60	60:40
Sericite and/or chlorite (%)	present	15–25	15–25
Carbon	significant	negligible	negligible
Accessory minerals	marcasite	marcasite	no mineralogical studies undertaken
	pyrrhotite	pyrrhotite	
	ilmenite	magnetite	
	cobalt arsenide	cobaltite	
	galena	galena	
	sphalerite	sphalerite	
	monazite	monazite	
	zircon	zircon	
	osmiridium	chalcopyrite	
	diamond	molybdenite	
	chromite	rutile	
	tourmaline	anatase	
	rare earths	rare earths	

Although there are striking differences in the average content of gold and uranium, and in the presence or absence of thorium and carbon, such geochemical variations are dominated by the similarity of geological features. To many geologists an explanation adequate to explain the origin of the ores in one district would be equally applicable to the other district. In fact, the discovery anywhere in the world of Proterozoic reef-type conglomerates in arenaceous sediments comprising closely packed small, glassy quartz pebbles and a pyritiferous matrix would immediately lead to investigations for gold and uranium. Therefore, genetically, such deposits may be related to a metallogenetic cycle restricted to a geological (late Precambrian) epoch.

This thought was expressed by the writer (1) several years ago when, with reference to the Canadian Shield, it was stated:

> The distribution of known pitchblende occurrences suggests that further efforts for new discoveries should be most profitably directed to the late Precambrian Proterozoic basins . . . including . . . the great Penokean geosyncline, extending from the basin of Lake Superior eastward north of Lake Huron. . . In any of these areas either pitchblende veins or radioactive sedimentary beds may be found.

At Jacobina geological studies are not sufficiently advanced or detailed to develop the concept of a metallogenetic cycle; but the comparative geological features of the reef conglomerates suggest a sequence of erosion, sedimentation, and mineral deposition that is similar and cyclical. Any acceptable theory of origin of the ores must be consistent with the principles of geochemistry (1), and the geochemical evidence is difficult to reconcile with a simple syngenetic hypothesis of origin. Neither is an exclusively hydrothermal origin acceptable to many geologists familiar with these deposits. Most workers admit some re-arrangement of the ore minerals and a large part of the accessory minerals. Therefore, it is important to determine the amount of "re-arrangement" that has taken place, and whether or not it has been sufficiently extensive to transgress the concept of epigenesis. In the meantime we can surely regard the banket gold-uranium deposits as the product of a metallogenetic cycle related to a sedimentation sequence within a restricted interval of geological time.

ACKNOWLEDGMENTS

The writer is indebted to G. F. Flaherty, whose geological work in the vicinity of the Canavieiras mine provided the first concrete evidence that the Jacobina gold deposits were, in fact, quartz conglomerate reefs bearing many similarities to the Witwatersrand bankets.

TORONTO, CANADA
January 29, 1958

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Economic Geology
Vol. 53, 1958, pp. 426–447

NICKEL–GOLD ORE OF THE MACKINAW MINE, SNOHOMISH COUNTY, WASHINGTON[1]

CHARLES MILTON AND DANIEL J. MILTON

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ABSTRACT

The Mackinaw mine ore is of an unusual or unique type, consisting chiefly of niccolite, maucherite, pentlandite, chalcopyrite, cubanite, and magnetite in an altered peridotite. Valleriite, gold and sphalerite are minor primary minerals; chalcocite and violarite or bravoite are supergene minerals. Pyrrhotite and pyrite are absent. From the textural relations it is inferred that a complex copper-nickel-iron sulfide was deposited early. On cooling, the sulfide unmixed into two different complex sulfides, one of which in turn unmixed into chalcopyrite and cubanite, the other into chalcopyrite and pentlandite. The latter exsolution relationship has not been previously reported. Valleriite either exsolved from, or replaced, chalcopyrite. Late solutions altered the niccolite to maucherite, and introduced gold and magnetite. The gold is almost always with maucherite.

INTRODUCTION

The Mackinaw mine, known locally as the Weden Creek mine, is in sec. 19, T. 29 N., R. 11 E., Snohomish County, Washington, in the Monte Cristo mining district, within the Mount Baker National Forest, 40 miles east of

[1] Publication authorized by the Director, U. S. Geological Survey.

Everett. The mineralized area is in a glacial valley at an elevation of 3,000 to 5,000 feet. The prospect was located in 1900, and development work has been carried on intermittently since then, especially during World War II.

J. J. Collins and S. C. Creasey, U. S. Geological Survey (written communication, 1944), state:

> The sulphide minerals occur as disseminated grains and blebs in the serpentine and may total as much as 20% of the rock in some spots. No concentration of sulphide minerals was noted on the numerous fractures in the serpentine, but the supergene oxide minerals, on the other hand, are concentrated on fault and fracture surfaces. The commonest of these minerals are probably malachite and garnierite, or annabergite, but erythrite is also much in evidence.

Further information from a Bureau of Mines report dated 1944 as follows:

> The ore deposits are in a peridotite dike or intrusive that appears to be an apophysis of the large intrusive of reddish-brown peridotite that comprises the mountain that rises southeast of the ore deposits. The peridotite is interspersed with small blebs and seams of serpentine, actinolite, and tremolite. At several places in the mass, small deposits of sulphide, which contain copper and nickel minerals, were observed. The peridotite, in which the principal ore deposits occur, is a dense, dark colored fine-grained rock that has been partly serpentinized. . . . The principal ore deposits occur in the peridotite along a shear zone that . . . dips nearly vertical . . . partly on the contact between the peridotite and metamorphic rocks, but parallel seams extend into the peridotite.

Spurr (16) investigated the geology of the Monte Cristo district in 1900, but did not mention the Mackinaw prospect, if indeed it had been located at the time of his visit. He reported that the chief ores of the district consisted of pyrite, pyrrhotite, arsenopyrite, sphalerite, galena, chalcopyrite, and realgar, and that gold and silver were present. Of course, this was at a time when polished sections and modern techniques of mineral identification were not yet developed and when maucherite was unknown and cubanite poorly known. A restudy of ores from other mines in the district may show that the mineralogy of the Mackinaw mine is not unique.

A brief summary of the mineralogical features, without discussion of the inferred history of the ore, was presented by Charles Milton at the Geological Society of America meeting, El Paso, Texas, 1949 (10).

Acknowledgments.—The present study has been made on a representative suite of ore specimens collected by S. C. Creasey, U. S. Geological Survey.

We are indebted to Dr. Gunnar Kullerud, of the Geophysical Laboratory of the Carnegie Institution of Washington, who has kindly read and instructively commented on this paper, without necessarily subscribing to the ideas contained in it. Professor A. F. Hagner, University of Illinois, furnished us typical specimens of the Alistos, Mexico, ore for comparative study. The critical X-ray diffraction identifications, without which this investigation would not have been possible, were made by Joseph M. Axelrod of the U. S. Geological Survey. The photomicrography was done by J. A. Denson, of the U. S. Geological Survey.

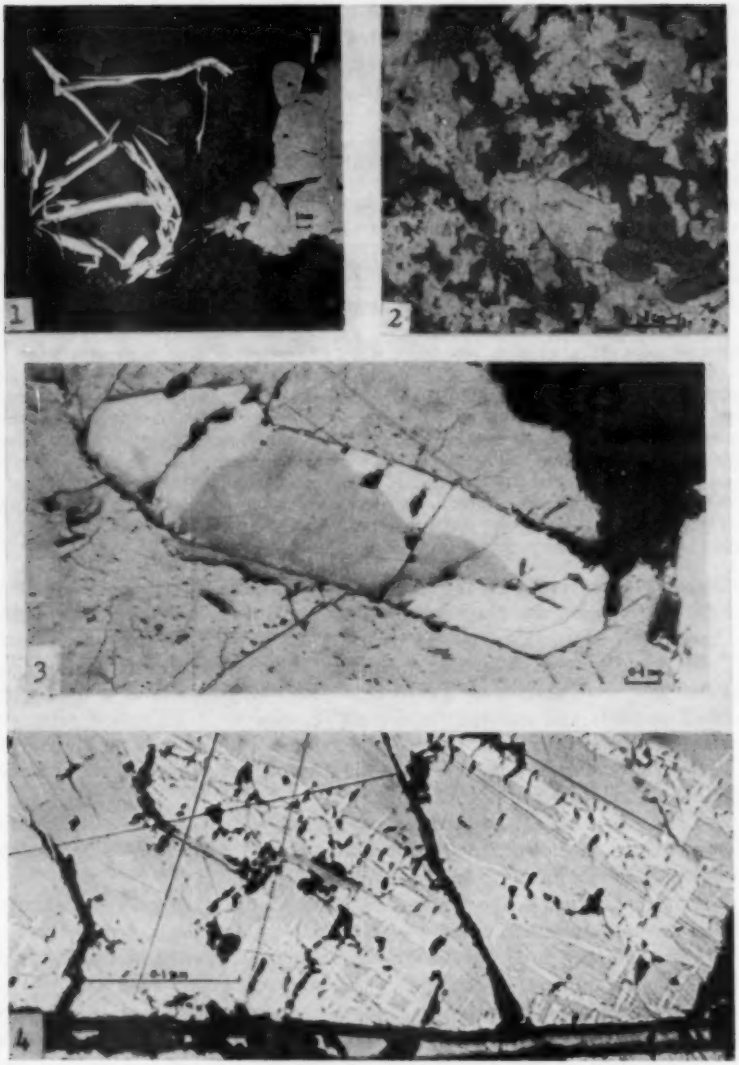

FIG. 1. At left, maucherite (light) rimmed by chalcopyrite (darker), with fine-grained chalcopyrite dispersed in gangue. At right, a massive aggregate of chalcopyrite-cubanite with pentlandite. × 2.

FIG. 2. Chalcopyrite-cubanite with minor pentlandite (light) and magnetite (darker gray) and gangue (dark). Natural size.

MINERALOGY OF THE MACKINAW MINE ORE

The ore minerals are generally strewn sparingly through the gangue. Although different from one specimen to another specimen, the gangue is mostly serpentine, and contains minerals common to altered ultramafic rocks, such as talc, actinolite, and carbonates, and oxidized ore minerals, such as malachite, annabergite, and erythrite.

The hypogene minerals at Mackinaw are the nickel arsenides (niccolite and maucherite), the nickel iron sulfide (pentlandite), and the copper iron sulfides (chalcopyrite, cubanite, and valleriite). Minor amounts of sphalerite, magnetite, and gold are present. Supergene alteration has produced a little chalcocite and covellite from the copper-iron sulfides, and bravoite or violarite from the pentlandite.

The arsenides and sulfides form more or less separate assemblages, and the gold is almost always associated with maucherite. When the mineralogy of this deposit was first studied, a small piece of ore examined in the Geological Survey laboratory was reported as containing major pentlandite, and no arsenides or gold; another piece of ore studied in another laboratory carried no pentlandite, but much maucherite with gold. Study of more specimens showed both assemblages to be closely associated in many of them.

Niccolite and Maucherite.—Niccolite (NiAs) is distinguished from maucherite ($Ni_{11}As_8$) by its bronze color; the maucherite, though it has a pinkish cast, is much paler. Moreover, niccolite is strongly anisotropic but maucherite is almost isotropic. The two minerals occur in crystal plates, commonly coalesced into irregular masses, and generally partially replaced by the other ore minerals. Some specimens contain maucherite without niccolite, but none were found that contained niccolite without maucherite. The occurrence of maucherite, separated from niccolite by a sharp boundary and generally on the outside, indicates that maucherite has replaced niccolite (Fig. 3). Alteration of niccolite to maucherite, by loss of arsenic, is also known at Los Jarales, Malaga, Spain, and Bou Azzer, Morocco (12), where, as in the Mackinaw ores, maucherite peripherally replaces niccolite.

No rods or blebs of maucherite in niccolite, such as those found at Alistos and interpreted by Krieger and Hagner (5) as exsolved, were found in the Mackinaw ore.

The occurrence in the oxidized ore of pink erythrite (cobalt bloom) as well as green annabergite (nickel bloom) suggests the presence of cobalt in some primary mineral or minerals. X-ray fluorescence examination shows a small amount of cobalt in the maucherite, and presumably cobalt is also present in the niccolite.

FIG. 3. Maucherite (lighter gray) replacing niccolite (darker gray). The left end of the large grain is also niccolite in a less extinguished orientation. Crossed nicols. × 50.

FIG. 4. Pentlandite lenses (white) in chalcopyrite, thinning at intersections. Pentlandite stops abruptly at a cubanite lamella (left, slightly darker than chalcopyrite). Magnetite in cracks (center and along bottom). × 260.

Pentlandite.—Pentlandite occurs in two major forms in the Mackinaw mine ore: as massive grains (Figs. 12, 14), and as flames and lenses in chalcopyrite-cubanite (Figs. 4, 5). A minor third form consisting of irregular small grains of pentlandite in a chalcopyrite-cubanite matrix, that do not have the regularity of shape of the flames or lenses, is probably the result of extensive replacement of massive grains of pentlandite by chalcopyrite-cubanite (Figs. 5, 6).

FIG. 5. Above, bands of pentlandite flames in chalcopyrite-cubanite. Below, right, chalcopyrite-cubanite, replacing pentlandite. Left center, pentlandite-chalcopyrite-cubanite in intergrowth of uncertain origin. Center, gangue and magnetite. × 70.

There was some difficulty in identifying the pentlandite. The relief indicates that it is somewhat harder than the adjacent chalcopyrite-cubanite but it is soft enough to be readily scratched by a needle (Talmage hardness of pentlandite D, chalcopyrite and cubanite C). It shows a rather vague cleavage. The mineral was confirmed as pentlandite spectroscopically and by X-ray diffraction; both examinations, including comparison with the X-ray pattern of pentlandite from Sudbury, Ontario, showed nothing anomalous.

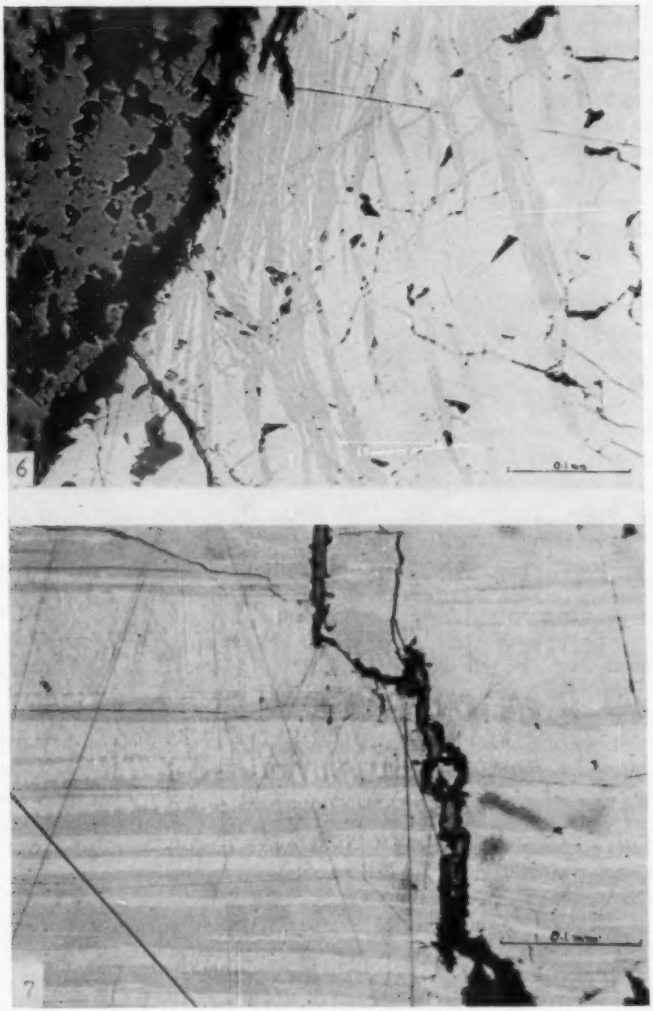

FIG. 6. Enlargement of lower right of Figure 5. Pentlandite white, chalcopyrite and cubanite gray. Magnetite in fracture above. × 200.

FIG. 7. Enlargement of upper field of Figure 5. Pentlandite white, chalcopyrite light gray (in bands with pentlandite flames), cubanite dark gray (between bands). × 225.

A very weak magnetism of some grains in the polished section, detected with McKinstry's magnet (7), might be due to underlying magnetite, cubanite, or perhaps valleriite, which are strongly magnetic. Minute particles, just visible to the naked eye, were tested with an alnico horseshoe magnet, and found to be definitely magnetic, probably because of intergrown cubanite.

The pentlandite is distinctly rose-colored, rather than pale yellow or cream like the usual pentlandite, as, for example, from Sudbury. This color may be merely an impression caused by the lack of contrast with pyrrhotite, against which pentlandite is usually observed. However, because the Mackinaw pentlandite is not associated with iron sulfides it may have a different composition from ordinary pentlandite, and this difference may be reflected in the color.

Violarite(?) or Bravoite(?).—The pentlandite is altered to a small extent to a gray-violet isotropic mineral of a slightly lower reflectivity than the pentlandite. This mineral is probably either violarite, Ni_2FeS_4, or bravoite $(Ni, Fe)S_2$. It characteristically occurs in irregular patches in the pentlandite, sometimes along fractures, and is itself crossed by a network of fine irregular fractures, apparently as a result of volume decrease during formation. This alteration is probably supergene.

Chalcopyrite and Cubanite.—Chalcopyrite is found in all the ore specimens, in three forms. In one form chalcopyrite, without cubanite, occurs as aggregates of many small irregular grains separated by gangue (Fig. 1). In its other major form chalcopyrite is in all cases intimately associated with cubanite, and commonly with pentlandite and valleriite. Chalcopyrite and cubanite are generally intergrown in parallel lamellae (Figs. 5, 9), but irregular intergrowths occur and chalcopyrite commonly replaces cubanite peripherally and along fractures (Figs. 9, 11). In a third form, chalcopyrite, alone or with magnetite or gold, replaces arsenides (Fig. 8).

Cubanite and chalcopyrite are of approximately equal hardness. They are easily distinguished by their characteristic colors, as cubanite has a bronzy tint against the yellow of chalcopyrite. The chalcopyrite is less anisotropic than the cubanite, and shows its usual complex twinning, which is not observed in cubanite. The excellent cleavage of the chalcopyrite terminates abruptly against the cubanite, which has a much poorer cleavage. A further distinction is in the relation of valleriite to these two, as described below.

Valleriite.[1]—Valleriite ($Cu_{2-3}Fe_4S_7$?), once considered rare but now recognized as common in high temperature (cubanite-bearing) copper ores, is beautifully developed in the Mackinaw ore. Its extraordinarily strong anisotropy and pleochroism and its characteristic feathery development in chalcopyrite make it easily recognizable (15).

The valleriite always occurs in the chalcopyrite rather than in the cubanite (Fig. 10), as is true, with minor exceptions, in all its occurrences (12). Val-

[1] Note added in proof: Preliminary results of studies in progress by C. Milton, E. C. T. Chao, and H. T. Evans, Jr., indicate that the mineral identified as valleriite in this paper is, in fact, distinct from the type valleriite from Kaveltorp, Sweden. The Mackinaw mineral is probably an undescribed iron sulfide, the Kaveltorp valleriite is perhaps a copper-iron-magnesium sulfide. Probably both these phases, if not others also, are to be found among material from other localities that has been called valleriite.

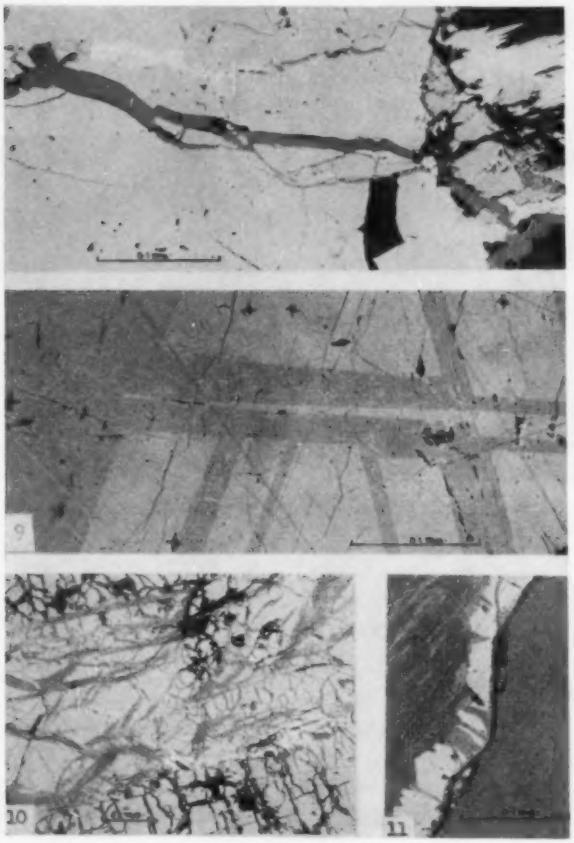

FIG. 8. Maucherite replaced by chalcopyrite-cubanite (right) and cut, above, by a vein composed of, left to right, chalcopyrite, gold and magnetite, and center and right by magnetite veins. × 200.

FIG. 9. Lamellar intergrowths of cubanite (dark) and chalcopyrite (light) with sphalerite stars and irregular bodies (right, very dark). Minor chalcopyrite replaces the cubanite along fractures. × 205.

FIG. 10. Cubanite (above and below) gray, and chalcopyrite (center), (slightly lighter). The chalcopyrite contains many "feathers" of valleriite. The valleriite is mostly replaced by chalcocite (dark gray), leaving only small patches unreplaced (below center, bright). The chalcopyrite and cubanite are also replaced by chalcocite and covellite (black). Crossed nicols, sensitive tint. × 75.

FIG. 11. Right, pentlandite. Center, unidentified mineral (valleriite?). Left, cubanite (dark) and chalcopyrite (light). Crossed nicols. × 175.

leriite also was found within a single grain of pentlandite as small ragged bodies all in parallel crystallographic orientation, perhaps aligned along a poorly developed cleavage in the pentlandite (Fig. 13).

Chalcocite and Covellite.—Minor amounts of chalcocite (or digenite) and even less covellite have formed from cubanite and chalcopyrite, along cracks.

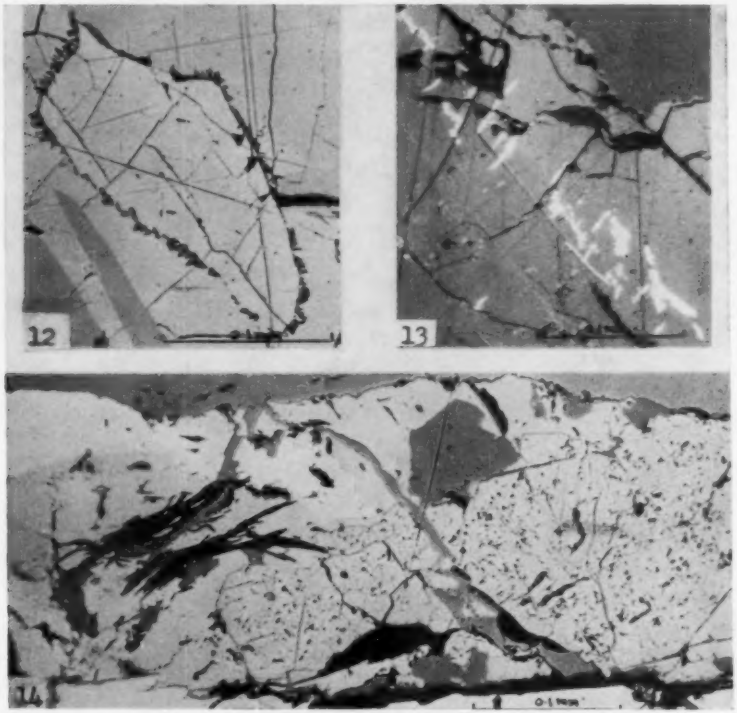

FIG. 12. Pentlandite grain mantled by sphalerite, in chalcopyrite (light)–cubanite (dark) intergrowth. × 260.

FIG. 13. Valleriite (bright) in pentlandite. Cubanite at upper right. Crossed nicols. × 225.

FIG. 14. Maucherite (brightest, left above and below), pentlandite (center and right, gray pitted surface), chalcopyrite (gray, smooth), sphalerite grains (dark gray, right above and below) and magnetite veinlets (dark gray). × 220.

The alteration is more marked in the cubanite than in the pentlandite; these copper sulfides are considered as of supergene origin. Chalcocite and covellite also replace valleriite, rather extensively.

Sphalerite.—Sphalerite occurs in tiny skeletal crystals ("stars") in the chalcopyrite-cubanite (Fig. 9). These are randomly distributed in the chalcopyrite and cubanite and across the boundaries, indicating that they formed

before the differentiation of those two minerals. Sphalerite stars are limited to high temperature ore deposits, but are well known in such.

Sphalerite also occurs as grains in chalcopyrite-cubanite. Most of them have rather simple rounded margins but some are of more complex shape, seemingly intermediate in a continuous series extending from the skeletal stars through less delicate skeletal crystals to the irregular and rounded blebs. Such sphalerite is commonly in the chalcopyrite-cubanite along the margins of pentlandite and magnetite grains (Fig. 12). There seems to be some crystallographic control of the localization and orientation of sphalerite grains and stars in the chalcopyrite-cubanite.

Magnetite.—There are two generations of magnetite. Magnetite of the older generation occurs mostly in small grains, disseminated in the gangue, some of which contain inclusions of gangue minerals themselves. This generation is probably more closely related to the normal magmatic stage of the peridotite than to the stage of ore formation. A very few corroded grains occur within the chalcopyrite-cubanite, and are probably relics of this earlier generation.

Magnetite of the younger generation occurs in veinlets cutting, or rims surrounding, all the other major opaque minerals (Figs. 4, 8). Silicate gangue, sometimes gold, and rarely chalcopyrite, are associated with the magnetite veinlets. Similar late magnetite was found at Insizwa by Scholtz (14).

Gold.—Gold occurs in considerable quantity in cracks or openings in maucherite, rarely in niccolite and cubanite. Typically it is in irregular, more or less rounded blebs in the maucherite, but it also occurs in veinlets cutting maucherite, generally with magnetite or chalcopyrite, in some places with valleriite also (Fig. 8). Its color is variable in golden shades, probably because of varying amounts of silver; for this reason, it might be called gold-electrum, rather than gold.

Other Possible Minerals.—Our belief in the absence of pyrrhotite rests on the failure to find a rose-colored mineral with fair cleavage, sensible magnetism, and definite anisotropy after thorough scrutiny of some two dozen polished sections. Some particles at first suspected of being pyrrhotite were proven to be pentlandite by X-ray methods.

One single group of grains suspected of being pyrrhotite is too small to be positively identified. These grains occur in cubanite-chalcopyrite along the edge of a pentlandite grain (Fig. 11). The mineral is rose-gray against cubanite and chalcopyrite, is weakly but distinctly pleochroic, moderately anisotropic in gray to reddish-brown, and has a reflectivity close to that of cubanite (but perhaps slightly more or less depending on orientation) and has no apparent cleavage. This mineral may be pyrrhotite, except for a slightly higher reflectivity, but fits as well or better for valleriite in a nearly basal section. It is probably valleriite of a somewhat unusual habit.

DEPOSITS OF SIMILAR MINERALOGY

A deposit at Alistos, Sinaloa, Mexico, described by Krieger and Hagner (5) in 1943 and considered by them to be unique has some points of similarity

to Mackinaw. At Alistos, the ore occurs in an enstatite latite, but on the periphery of, and associated with, an altered peridotite intrusive. Here, too, pentlandite occurs without pyrrhotite (although with pyrite). At Alistos, moreover, two distinct types of ore were found, one containing nickel arsenides (mostly niccolite) but no nickel sulfides, the other nickel sulfides but no nickel arsenides. Gersdorffite (NiAsS) occurs in both types. Most of the gold is present in arsenide ore. The Alistos deposit, however, differs markedly from the Mackinaw deposit in the absence of copper minerals.

The ores of Insizwa, South Africa, in the basal part of a mafic intrusive, described by Scholtz (14), also have some features in common with the Mackinaw ores. At Insizwa, most of the ore contains abundant pyrrhotite, but there also occur pyrrhotite-free ores. One type, "massive chalcopyrite-cubanite ore," consists of about 50 percent chalcopyrite, 30 percent pentlandite, 18 percent cubanite, and 2 percent bornite and other unnamed minor constituents. The deposit as a whole is regarded as of magmatic origin, and the chalcopyrite-cubanite ore as representing a late copper-rich differentiate. Textures and relationships in the Insizwa ore are commonly similar to those in the Mackinaw ore. The Insizwa ores differ from the Mackinaw ores in that arsenides (niccolite) and gold are comparatively scarce, and, of course, the Mackinaw ore is entirely pyrrhotite free, whereas the chalcopyrite-cubanite ore at Insizwa is a rather aberrant type within a pyrrhotite-rich deposit.

RELATIONSHIPS OF THE SULFIDE MINERALS

The Mackinaw deposit is unusual, perhaps (excepting Alistos) almost unique, in containing pentlandite without pyrrhotite.

The cause of this absence of pyrrhotite will be discussed in detail below, but in brief, it, as well as many of the other unusual features of the ore, can be attributed to the exceptionally high Ni:Fe and Cu:Fe ratios of the Mackinaw ore. Thus, our explanation of the development of the ore, which we feel is in accord with the evidence of the polished sections, must differ in some particulars from any that has been proposed for other ore deposits.

Most of the chalcopyrite, cubanite, and valleriite, and some of the pentlandite and sphalerite are interpreted as having unmixed from an originally homogeneous solid sulfide phase of complex composition, which we may call "phase I." From the relative abundance of its unmixing products, phase I is inferred to have contained copper, iron, and nickel sulfides in proportions that would very approximately give about equal parts of chalcopyrite and cubanite, and about a fourth as much pentlandite, and perhaps also small amounts of zinc sulfide.

On cooling, phase I unmixed into an intergrowth to two new phases, II and III, each of which later underwent further unmixing. Phase II, a copper-nickel-iron sulfide, formed as lamellae within, and as less regular areas along the edges of, the more abundant phase III, a copper-iron sulfide. Figure 15 shows the inferred course of exsolution for the minerals derived from phase I. An idea of the inferred composition of phase I may be obtained from Figure 16A and of phases II and III from Figure 16C. It must be understood that phases I, II, and III are only inferred, by the reasoning given below.

On further cooling phase II unmixed into mostly chalcopyrite and pentlandite, the latter characteristically in flames transverse to the phase II lamellae (Figs. 5, 7). In areas of coarser texture the flames thin at intersections (Fig. 4), generally regarded as an indication of origin by exsolution. Many bands of pentlandite flames are broader than the associated chalcopyrite lamellae, and extend into cubanite, a mineral that for the most part formed from phase III. Some bands of pentlandite flames even seem to be entirely in cubanite, although it is sometimes difficult to determine the mineral between the pentlandite grains in the finer-textured intergrowths. At each higher magnification up to the limit of resolution, the interstitial mineral in more and more bands of pentlandite flames seemingly in cubanite can be identified as

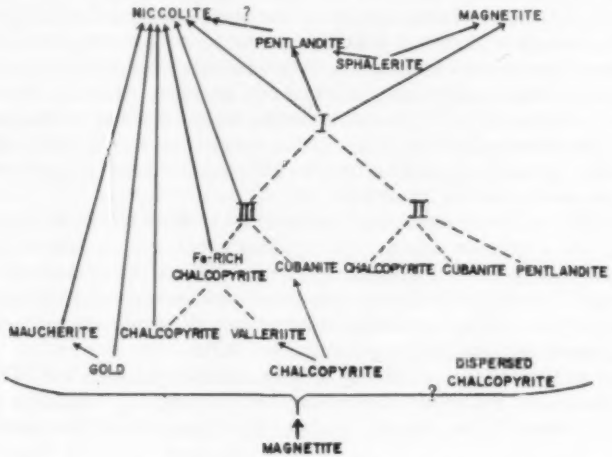

FIG. 15. Paragenetic relations of Mackinaw ore minerals. The dotted lines indicate exsolution or unmixing relationships. Solid lines indicate replacement or rimming, the arrow pointing to the older mineral.

chalcopyrite. On the other hand, some bands still seem to have very little associated chalcopyrite. However, the association of the pentlandite bands with chalcopyrite rather than cubanite is so dominant that it must be regarded as the normal occurrence. It is more likely that all the pentlandite exsolved from phase II, which contained varying amounts of excess iron that separated as cubanite, than that some of the pentlandite exsolved with cubanite from phase III. If so, the composition of phase II would correspond to a mixture of about equal parts of chalcopyrite and pentlandite and perhaps a tenth part of cubanite.

Certain patches of pentlandite that occur in either chalcopyrite or cubanite or both may be confused with the unmixed phase II. These patches consist of irregularly shaped pentlandite grains enclosed in a nearly patternless network of the copper sulfides and never arranged in bands. These patches are

probably the result of extensive veining and replacement of pentlandite grains that formed as such before the deposition of phase I, because intermediate stages seem to be present. However, similar textures may have arisen on unmixing of phase II. The origin of part of the intergrowth shown in Figures 5 and 6 is indeterminate for this reason.

No material corresponding to phase II or its exsolution product has been reported, either naturally occurring or artificially produced. The only exsolution relationship involving pentlandite and chalcopyrite mentioned by Ramdohr (12, p. 150) consists of a *"zellig-netz-formig"* (cell-net form) intergrowth of one part of chalcopyrite in ten parts of pentlandite from Igdlokunguak, Greenland. He comments that this is rare as an exsolution texture but that similar textures are produced by replacement. Elsewhere (12, p. 85), he has a photograph of an ore from the same locality containing material in which no internal structure can be seen; according to his caption this material is an almost isotropic complex mixture of pentlandite and chalcopyrite (originating from an (Fe,Cu,Ni)S mix-crystal). It is not clear whether these two references are to the same material, but in any case, neither resembles the Mackinaw intergrowths. No sulfides containing copper and nickel have been found by study of artificial mattes (8), nor are any copper-nickel-iron sulfides mentioned in the literature.

Phase III was a copper-iron sulfide with little or no nickel, that eventually unmixed into a lamellar intergrowth of about equal quantities of chalcopyrite and cubanite (Fig. 9). This chalcopyrite is quite distinct from that formed from phase II because it has no associated pentlandite. Such chalcopyrite-cubanite intergrowths are well known from many localities, although elsewhere the chalcopyrite is generally in great excess (12).

There was probably a continuity of state between phases I and III, that is, the composition of the solid solution changed continuously from that of phase I to that of phase III as a consequence of the separation of the quite distinct phase II.

After the unmixing of phase III, valleriite formed from the phase III chalcopyrite. The textures are very similar to those found by Scholtz, in which valleriite "half feathers" developed entirely or almost entirely in chalcopyrite, especially along the boundaries of cubanite lamellae (Fig. 10). The valleriite probably formed by exsolution although the textures could have been developed by replacement as well. The amount is well within the range given by Ramdohr (12) for the extent of exsolved valleriite in chalcopyrite (up to 10 percent).

Minor late chalcopyrite is present within cubanite and valleriite. As this chalcopyrite is along crosscutting cracks (or cleavage in the valleriite) it probably represents a replacement rather than an exsolution product.

The greatest part of the pentlandite occurs not as exsolved bodies, but as independent grains, at least contemporaneous with, and some earlier than, phase I. Lenses of chalcopyrite and cubanite, probably the exsolution products of an original phase III, occur within the pentlandite (Figs. 5, 6). The curved lenticular shape and the lack of relation to visible cracks might suggest exsolution from the pentlandite. However, the irregular distribution, the vary-

ing abundance, and the concentration of the lenses toward the margins of the pentlandite suggest much more strongly the replacement of pentlandite by phase III. The origin of the one example found of valleriite in pentlandite is also indeterminate although the irregular distribution suggests replacement (Fig. 13). Exsolved valleriite is common at other localities; Ramdohr reports pentlandite containing up to 25 percent of exsolved valleriite (11).

The random distribution of sphalerite "stars" within chalcopyrite and cubanite and across the boundaries between them (Fig. 9) indicates that the stars formed before the unmixing of phase III. The method of formation of sphalerite stars has never been definitely established. When Ramdohr (11) first described them, he was inclined to attribute them to mechanical inclusion of ZnS during rapid growth of the copper-iron sulfide. More recently (12) he has tended to favor an origin by exsolution. As mentioned above, there seems to be a continuous gradation from the stars to the grains of sphalerite. The latter show no indications of exsolution, but instead their irregular distribution, range of sizes, and marked preference for the margins of ore minerals that are replaced by the phase I minerals (Fig. 12), suggest that the main period of formation of sphalerite grains coincided with or preceded the beginning of deposition of formation of phase I. Whether the stars are of the same origin or are exsolved is an open question. The total amount of sphalerite is only a fraction of one percent of the amount of the phase I minerals.

As the history of the Mackinaw ore is quite different from that of any other known deposit, comparative studies are of little help in understanding the paragenesis. There has been no experimental work on the quaternary system Cu-Ni-Fe-S although some data are available on the ternary systems Cu-Fe-S (9, 2) and Fe-Ni-S (4, 6). Therefore, there is little except the observed relations and some rather incidentally applicable experimental work to aid in the interpretation of the paragenesis, in particular the nature and history of the phase I complex.

At about 540° C, the copper and iron atoms in chalcopyrite disorder, and the disordered phase has a sphalerite-type crystal structure (3). The tolerance for a high ratio of iron to copper and the tolerance for other metals—tin, zinc, and presumably nickel—increase. Phase III is very likely such an iron-rich disordered chalcopyrite, and probably phase I is a nickelian variety of the same. However, until this suggestion is confirmed by experimental work, it seems best not to use mineral names for these hypothetical phases.

Phase II is more difficult to explain. The relative amounts of pentlandite and chalcopyrite in its unmixed derivatives suggest a compound with a Cu:Ni:Fe:S ratio of about 1:1:2:4. That no such material has been found naturally, as either a mineral or its unmixed equivalent, is understandable on the basis of the different overall composition of Mackinaw ore from that of other investigated deposits. However, if such a substance exists, it might be expected to occur in artificial mattes, but it has never been reported. It is possible that phase II, as well as phase III, is a chalcopyrite-type mineral. Even its stable coexistence with phase III does not preclude the possibility that there is a continuity of state between them, even at the same temperature

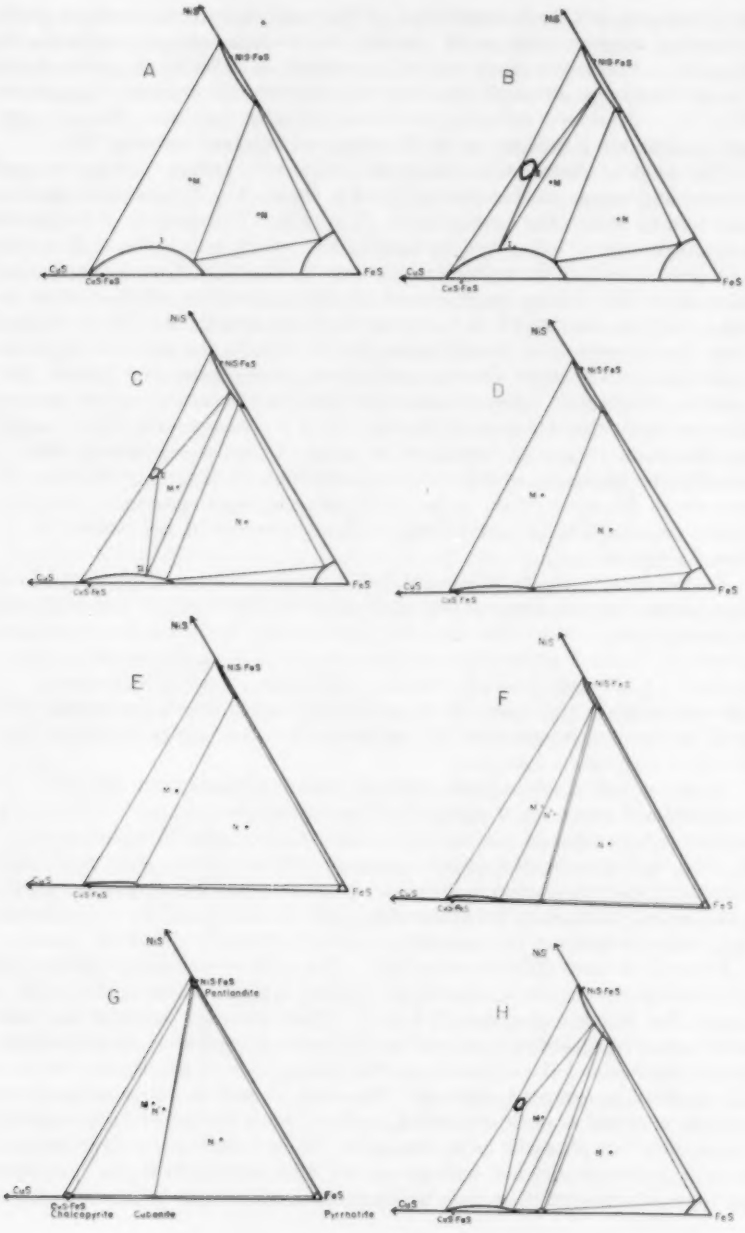
A
B
C
D
E
F
G
H
NiS
Ni3 FeS
CuS
Cu5 FeS
FeS
Pentlandite
Chalcopyrite
Cubanite
Pyrrhotite

FIG. 16.

and pressure. However, as there is no evidence on this point, in Figure 16 we merely indicate the inferred composition of the phase present in the Mackinaw ore.

Borchert (2) studied unmixing in the Cu-Fe-S system experimentally. His findings are summarized in Figure 17. The solid solution that is stable only at temperatures above 255° C, but preservable to room temperature by rapid chilling, he called chalcopyrrhotite. The range in composition of chalcopyrrhotite shortens with decreasing temperature until a composition about midway between cubanite and pyrrhotite is reached at the eutectoid, 255° C. Below this temperature, only chalcopyrite and pyrrhotite are stable but cubanite and valleriite become stable in that order on still further cooling. Thus, the cooling history of a material in the chalcopyrite-pyrrhotite system (especially in the copper-rich end) would be quite complex.

Borchert also found a naturally occurring mineral which he identified as chalcopyrrhotite. The fullest discussion of chalcopyrrhotite as a mineral is given by Ramdohr (12), who has identified it from many localities. It is isotropic, or very weakly anisotropic, brownish like pyrrhotite but somewhat more yellowish, and has a similar reflectivity. It occurs alone or intergrown with chalcopyrite or cubanite. Nickel may enter into chalcopyrrhotite and, Ramdohr believes, may increase its stability at low temperature. No X-ray investigations of chalcopyrrhotite have been made, but Ramdohr believes it probable that chalcopyrrhotite has the disordered chalcopyrite structure. Such a structure, however, seems rather unlikely for a substance that has, at the lowest temperature of stability, as high an Fe : Cu ratio as chalcopyrrhotite. If the shoulder on the chalcopyrite-chalcopyrrhotite solvus at about 325° C

FIG. 16A to H. Inferred equilibrium assemblages during development of copper-nickel-iron sulfide ores. These are pseudo-ternary diagrams, as the minerals may not be stoichiometric and so would not lie on a plane. Point M shows the overall composition of the Mackinaw ore; Point N that of the normal (Sudbury) type ore, point N′ (on 16 F and G) another possible type.

FIG. 16A. An early stage, in which the Mackinaw assemblage consists of pentlandite and phase I. Phase II is unstable at this temperature.

FIG. 16B. Phase II is assumed to be stable, but M lies outside its stability field. This may be an alternative or a successive stage to that of 16A.

FIG. 16C. A later stage, in which the Mackinaw assemblage consists of phase III, phase II and pentlandite.

FIG. 16D. A stage after the disappearance of phase II. Pentlandite and a compound near chalcopyrite form from the breakdown of phase II. Although there is a complete solid solution between chalcopyrite and phase III, both phases persist in disequilibrium.

FIG. 16E. A later stage before the appearance of cubanite, in which the extent of solid solution has decreased.

FIG. 16F. A stage after cubanite becomes a stable phase, although not for ore of the composition of the Mackinaw ore. N and N′ indicate two possible cubanite-bearing ores.

FIG. 16G. A late stage in the history of the Mackinaw ore, with an assemblage of nearly pure chalcopyrite, cubanite and pentlandite.

FIG. 16H. A possible equilibrium assemblage, alternative to those of the preceding diagrams. Here phase II and cubanite are stable under the same conditions, but not for the same overall compositions.

reported by Borchert (Fig. 17) has any existence, it may indicate a phase change, perhaps from a chalcopyrite structure to some unknown chalcopyrrhotite structure.

The relationship of our phases I, II, and III to chalcopyrrhotite is not clear. At high temperatures there may be complete solution between the compositions of all these materials. Borchert's diagram indicates that chalcopyrrhotite must form during the cooling of a CuS-FeS mixture with any significant excess of FeS over that necessary to form $CuFeS_2$ and that chalcopyrrhotite in turn must unmix to pyrrhotite and either chalcopyrite or cubanite or both. Neither chalcopyrrhotite nor pyrrhotite was found in the Mackinaw ore. One might possibly regard phase II as a nickelian chalcopyrrhotite that unmixed to chalcopyrite and pentlandite rather than to chalcopyrite and pyrrhotite. However, until the nature of chalcopyrrhotite and other phases in this system are better understood it seems best not to extend Borchert's and Ramdohr's usage but to use noncommittal terms for other solid solutions. Borchert's diagram shows chalcopyrite and cubanite to be stable together only between 225° and 235° C. To account for the lamellar intergrowth of these two minerals, from his diagram, it is necessary to assume that the Mackinaw ores, as well as almost all other chalcopyrite-cubanite bearing ores, were completely reconstituted between these temperatures, and that all the pyrrhotite and/or chalcopyrrhotite (which must have been present according to Borchert's diagram) completely reacted with chalcopyrite to form cubanite. Below 225° C cubanite and chalcopyrite would be unstable together, and should react to form valleriite. However, this reaction proceeded to a very slight extent. This history is improbable to the point of impossibility. The common occurrence of chalcopyrite-cubanite intergrowths strongly suggests a solvus (represented by the unmixing of our phase III) with ends at the chalcopyrite and cubanite compositions rather than at the chalcopyrite and chalcopyrrhotite compositions. Just what chalcopyrrhotite is, is an extremely interesting problem, but there is no reason to believe a phase fitting Borchert's conception of chalcopyrrhotite was at any time present in the Mackinaw ore.

PARAGENESIS

A diagrammatic representation of the paragenetic relations is given in Figure 15. The scheme of the diagram is somewhat similar to, although simpler than, that of Robertson and Vandeveer (13). Solid lines indicate a replacement or a rimming relationship, and the arrow points to the older mineral. Dotted lines indicate exsolution relationships. If both solid and dotted lines extend upward from a mineral, it means that the mineral formed by exsolution and, at about the same time, was deposited directly, replacing or rimming other minerals as shown. Generally, the downward direction indicates decreasing age, but no attempt has been made to indicate the extent of the period of formation of each mineral, as is done on the usual paragenetic line diagram. For the sake of clarity, some of the less critical observed relations have been omitted.

Successive stages in the development of the sulfides in the ore, are shown on eight triangular diagrams in Figure 16. Similar diagrams have been

widely used in understanding igneous and particularly metamorphic rocks in light of the phase rule restrictions on mineral associations. However, they have been little used for ore deposits, perhaps because of a feeling that these are not equilibrium assemblages and so are not subject to the phase rule. Recently, opinion has been changing toward the viewpoint that ore deposits, cautiously interpreted, can be regarded as near enough to equilibrium assemblages to allow the use of phase rule diagrams, which, indeed, help to point out disequilibrium when it is present. Betekhtin (1), in particular, has developed such diagrams and presented a series showing the more common assemblages in hydrothermal deposits. He plotted the commonly occurring assemblages of the Cu-Fe-Ni-S system (none like the Mackinaw association, of course) on the projection of a tetrahedron.

A triangle, rather than a tetrahedron, can be used if the compositions of all phases involved lie on a plane within the tetrahedron. Cubanite has a nearly stoichiometric 1 : 1 metal-to-sulfur ratio, pyrrhotite generally has a sulfur excess, pentlandite and perhaps chalcopyrite are sulfur deficient. Therefore, a plane can be passed through the Cu-Fe-Ni-S tetrahedron that will pass near the points representing these phases. The vertices of the triangle are close to, but not exactly, CuS, FeS, and NiS, although Figure 16 has been so labelled for convenience. The deviation of the composition of the minerals from the plane is assumed to be so small that it has no effect in determining the equilibrium assemblages, that is, only three phases can coexist stably in the system at an arbitrary temperature and pressure. Valleriite, however, probably has a sufficiently different metal-to-sulfur ratio that, like pyrite, it cannot be plotted on the plane diagram, but must be considered separately.

There are three types of regions in triangular diagrams: one-phase fields that denote the extent of solid solutions; two-phase fields, in which the equilibrium assemblage consists of a solid solution lying at one end of the field and either a solid solution or a compound of fixed composition at the other; and finally, three-phase fields, in which the equilibrium assemblage consists of the phases (compounds or fixed members of a solid solution) lying at the vertices of the triangular field.

Each triangular diagram indicates the equilibrium assemblages only at specific conditions of temperature and pressure. In the system under consideration, pressure is probably of secondary importance. The metal-to-sulfur ratios of the phases are so nearly the same that reactions between them may be considered as taking place at a constant partial pressure of sulfur. Therefore, the sequence of diagrams of Figure 16 may be considered as representing our idea of the change of equilibrium assemblages with changing temperature. It must be emphasized that these diagrams are entirely inferred, drawn so as to present a reasonable interpretation of the mineral relations of the Mackinaw ore.

Niccolite, pentlandite, and the rare early magnetite are the oldest ore minerals. Relations such as those in Figure 14 suggest that pentlandite is later than niccolite, but this age relation cannot be proven. Phase I and sphalerite are later than the pentlandite; sphalerite tends to be the earlier of

the two as it is usually immediately in contact with the pentlandite (Fig. 12). Of course, there may be considerable overlap in the paragenetic sequence. This stage, characterized by the deposition of the greater part of the ore minerals, as contrasted to the alteration of pre-existing ore minerals, may be considered the early stage. Two slightly different alternative diagrams (Fig. 16, A and B) show the assemblage during the early stage. Point M represents the approximate overall composition of the Mackinaw ore, and point N that of the more common nickel-copper ores, such as that of Sudbury. The ore (in addition to the minerals such as niccolite, which cannot be plotted on our diagram) is composed of pentlandite and phase I, which, if it is structurally a disordered chalcopyrite, would lie on the edge of a solid-solution field extending at least to the chalcopyrite composition. Either phase II is not stable at these temperatures (Fig. 16A) or it is stable but the composition of the ore is not within its stability field (Fig. 16B).

The separation of phase I into phases II and III was the first event of the intermediate stage (unless some sphalerite exsolved from phase I). Figure 16C shows the assemblage after this event. As a consequence of the retraction of the chalcopyrite solid-solution phase field back toward the nickel-free side of the triangle and as consequence of either the appearance of phase II as a stable phase or of the extension of its stability field toward the right, the ore composition point M finds itself in the three phase field, II–III–pentlandite. Chalcopyrite-cubanite intergrowths replace the arsenides and pentlandite, and it is reasonable to suppose that the actual replacement occurred when these minerals formed a solid solution (phase III), and the unmixing took place later. The overall composition of the ore probably was continually changing by reaction with a fluid phase, but these changes were probably small enough not to prevent plotting point M in the same place on each diagram.

Subsequently phases II and III each separated into their unmixing products. One of the simpler of the alternative possible sequences of events is given by Figure 16C, D, E, F, and G. In this sequence, first phase II became unstable, unmixing into pentlandite and chalcopyrite, the latter with a slight excess of iron that eventually appeared as cubanite, as discussed in the preceding section. Figure 16D shows the situation after the disappearance of phase II. Both before and after this stage, the maximum possible content of iron in the chalcopyrite-phase III solid solution was constantly decreasing, as is illustrated by the change from Figure 16D to 16E. Note that for ore of the composition shown at point N, iron is released and appears as pyrrhotite but M is still within the two phase field. Finally, cubanite appears as a stable phase. Figure 16E shows the situation before and Figure 16F soon after its appearance. As cooling continues toward the final stage of Figure 16G, the excess iron is almost entirely expelled from the chalcopyrite and appears as cubanite.

Three ore assemblages are possible in the system. From point M we get an equilibrium assemblage of pentlandite-cubanite-chalcopyrite, as we find at the Mackinaw mine. From point N we get an equilibrium assemblage of pentlandite-cubanite-pyrrhotite with chalcopyrite as a disequilibrium mineral

relict from stage 16E. This assemblage is probably the most common in ore deposits throughout the world. Finally, from point N′ we get an equilibrium assemblage of pentlandite-cubanite-chalcopyrite, with pyrrhotite as a disequilibrium relict mineral. This assemblage probably also occurs, but less commonly than the preceding.

Figure 16H is a variant that illustrates one of the numerous possible alternative sequences of events that are in accord with the textural evidence. Here, phase II remains stable until after the appearance of cubanite. Experimental work is necessary to decide between such alternatives.

Not only the major changes in the system, such as the appearance or disappearance of phases, but the details of equilibrium diagrams, such as the

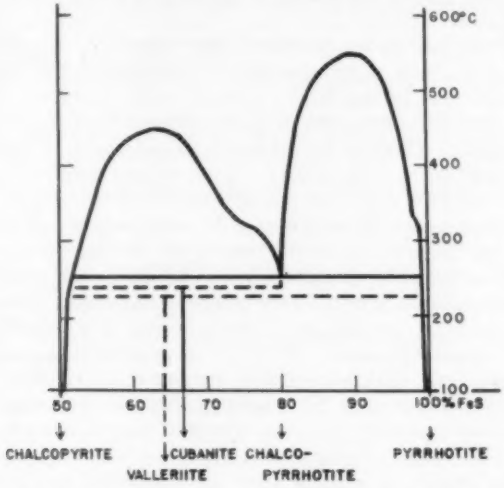

FIG. 17. Cu-Fe-S system, between $CuFeS_2$ and FeS (after Borchert).

exact composition of solid solutions in equilibrium with other phases—for instance the exact composition of phase III in equilibrium with phase II and pentlandite—are each associated with a definite temperature (if pressure and other variables are considered unimportant). Therefore, such ores as that of Mackinaw mine contain a record of the temperatures at which each feature developed. Experimental work is necessary to enable us to determine what these are.

Some time in the later stages of this process, valleriite exsolved from (or perhaps replaced) chalcopyrite. Probably the critical factor controlling the appearance of valleriite is the sulfur pressure. If so, it is very misleading to ignore the deviation from the 1 : 1 metal-to-sulfur ratio and to project valleriite onto a diagram between chalcopyrite and pyrrhotite, as Borchert did. It is possible, however, that sulfur pressure is not important but that valleriite is a late phase occurring in a disequilibrium assemblage in the CuS-FeS-NiS

system, as we have suggested for cubanite at Sudbury. Simply knowing the correct composition of valleriite would go a long way toward answering these questions.

Still later, chalcopyrite replaced (or perhaps exsolved from) cubanite and valleriite. Replacement, if it occurred, was probably caused by later solutions, richer in copper.

The arsenides are replaced not only by chalcopyrite-cubanite (phase III) but by a few composite grains of chalcopyrite and valleriite and commonly by chalcopyrite alone (Fig. 15). These relations indicate that the replacement occurred not only during the period of stability of phase III, but during the period of stability of chalcopyrite with dissolved excess iron (later exsolved as valleriite), and during the period of stability of chalcopyrite and valleriite as separate phases.

Almost all the gold is within maucherite. Not only is gold very rare in niccolite but it is much more abundant in maucherite that has completely replaced niccolite than in maucherite that only rims niccolite. This distribution suggests that the same solutions that extracted arsenic from the niccolite deposited the gold. There is no indication of exsolution of gold from maucherite. The gold in the maucherite is commonly associated with chalcopyrite, in places together with valleriite, but apparently never with cubanite. This association indicates that deposition of gold commenced after the breakdown of phase III but extended from the period of stability of the chalcopyrite-valleriite solid solution into the period when only pure chalcopyrite was stable. Magnetite veins and rims almost all the other ore minerals. From its common occurrence in fracture openings, it seems to belong to a definitely later stage than the other opaque minerals. However, association of a small part of the gold and a very little chalcopyrite with magnetite in veinlets indicates the persistence of the formation of these minerals into the late stage. The magnetite is commonly separated by a thin screen of gangue from the arsenide or sulfide that it rims, which indicates that there has been slight replacement of the arsenide or sulfide by gangue after the magnetite deposition, with the magnetite undisturbed by the replacing solutions.

The fine-grained chalcopyrite disseminated in the gangue shows no textural relationships to other ore minerals that would indicate its place in the sequence. However, if it were contemporaneous with the earlier copper sulfides, it would be expected to have contained excess iron, as they did, which would eventually have exsolved as cubanite or valleriite. Because cubanite and valleriite never occur with the disseminated chalcopyrite, it seems most reasonable to attribute formation of the last to a time when chalcopyrite in the rest of the ore contained no excess iron. If the disseminated chalcopyrite formed as late as the magnetite, when excess iron would be deposited as the oxide rather than as a sulfide, the absence of directly precipitated, as well as exsolved, cubanite and valleriite is easier to explain.

Finally, bravoite(?) or violarite(?) replaces pentlandite and chalcocite and covellite replace the copper sulfides. These are late, probably supergene, minerals.

U. S. Geological Survey,
Washington, D. C.

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Economic Geology
Vol. 53, 1958, pp. 448–472

EN ECHELON FOLDING

J. D. CAMPBELL

ABSTRACT

In the folding of layered rocks, varying responses to the deforming forces must soon give rise to complexity in the stress system. An analysis is presented to show that this can lead to the development of *en echelon* effects in the fold pattern.

The simplest *en echelon* pattern is where a series of minor synclines breaks obliquely through a larger anticline, or where a series of minor anticlines breaks through a larger syncline. The interference caused by the minor folds produces a zig-zag pattern in the axial trend of the main fold, and the crest of an anticline or the trough of a syncline becomes a series of overlapping minor folds, offset from one another in an *en echelon* pattern. More profound effects arise where both an anticline and a syncline are involved in an *en echelon* change. This produces a series of fold blisters forming a larger fold that is oblique to the attitudes of the lesser folds of which it is constituted. This type is described as an elliptical pattern of *en echelon* folding.

The zig-zag type can be grafted onto an elliptical series to produce a more complex form, the characteristic feature of which is that a strong fold can break down in a relatively short distance into a series of inconspicuous minor folds. From these, there emerges a new major fold offset to one side from the line of the original fold. Examples drawn from Australian mines are given for the various types of *en echelon* folding.

INTRODUCTION

To illustrate the development of *en echelon* effects in arcuate mountain ranges, S. Tokuda (3) mounted rice paper on a layer of soft paste and exerted pressure on the paper with his thumb. One of his illustrations is sketched in Figure 1a. Considering only the right-hand half of this sketch, where *en echelon* folding is well developed, the active force is the advance of the thumb, which causes the rice paper in front of it to slide over the base on which the paper is mounted (Force F, Fig. 1a). The inactive mass of paper to the right is equivalent to a complementary force F′, so that the initial stress system is comprised of the forces F–F′. Their effect can be demonstrated with a cloth, laid on a table top and pushed in the appropriate directions with the hands. The result is a fold-like crumpling, aligned as in Figure 1b.

The stress system in Tokuda's experiment is more complex than this, however, because movement along F tends to drag the rice paper in towards it. On the other side of the fold, adhesion of the rice paper to the paste on which it is mounted causes a resistance to this dragging effect. In combination, these two can be regarded as producing a second set of forces S–S′, which are directed along the flanks of the developing fold (Fig. 1a). Returning to

the cloth on the table top, forces S–S′ would, by themselves, produce folding aligned as in Figure 1c.

An explanation of Tokuda's experiment could be that the initial result was the development of a fold caused by the forces F–F′ but that, at an early stage, the induced forces S–S′ developed sufficient strength to dominate the detail of fold formation. These secondary folds could develop, however, only

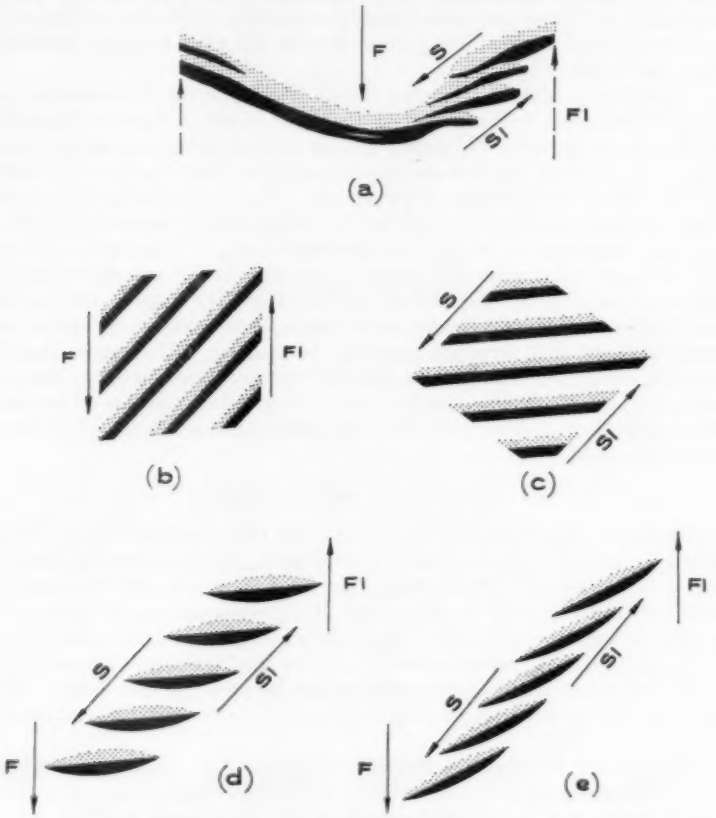


FIG. 1. An analysis of experimentally produced *en echelon* folding.

to the extent to which they conformed to the trend of the main fold. As a result (Fig. 1d), there was developed a series of short folds, individually sympathetic with the folding direction of Figure 1c but forming, in the aggregate, a fold of the alignment required by Figure 1b. These secondary folds then took up all further deformation but, in doing so, increased the overall development of the primary fold while preserving its basic shape. As the

folding progressed, the combined effect of the forces F–F′ and S–S′ was to rotate the axes of the *en echelon* folds more and more towards the axial direction of the main fold (Fig. 1e).

This analysis has aimed mainly at showing that, although the stress system contained an element of complexity, there is order and simplicity in the folding —a larger fold made up of a left-hand *en echelon* pattern of smaller folds. Turning to natural conditions, it is probable that a stress system would develop complexity as folding progressed, even in relatively simple fold structures, and it is certain that severe folding must involve the most complex interplay of stress and strain.

In detailed studies of a number of fold systems in the Precambrian greenstones of Western Australia and in Paleozoic rocks in Eastern Australia, it has become apparent to the writer that *en echelon* effects are major features of the fold patterns, and that an understanding of them is a key to structural analysis and to the guidance of ore search. The interpretation of *en echelon* folding is made difficult, however, by the complexity of the detail, which confuses the issue even where the data available seem, at first sight, to be more than adequate. To meet this position, the need is for an understanding of basic patterns of *en echelon* folding, so that diagnostic features can be recognized and predictions of behavior can be made, even though a conclusive interpretation of the fold structure may not be possible. This paper describes, therefore, some idealized patterns that are thought to be useful guides to the nature and characteristics of *en echelon* folding, which also are of interest in the interpretation of structures of mining areas. Examples are given for each type of behavior.

EN ECHELON FOLD PATTERNS

Zig-Zag Pattern.—Figure 2 presents the main features of an idealized pattern for a right-hand *en echelon* change in an idealized anticlinal fold. In this, as in subsequent illustrations, the diagram shows the behavior of a single thin bed. Figure 2a gives a set of eight evenly spaced cross-sections through the area of fold change; Figure 2b is a longitudinal projection showing the plunge lines of the anticlinal crests and synclinal keels; and Figure 2c gives in plan projection the changing relationships between the fold axes.[1] Figure 2d is a block diagram giving a clearer picture of the overlapping and changing shapes of the folds.

Cross-section H–H shows the original anticline A1 before the *en echelon* change commences. In cross-section G–G, an embryo anticline A2, with its accompanying syncline S1, is forming on the right-hand flank of A1. In sections F–F and E–E, A2 has increased and A1 has decreased in size; in section D–D, A2 has become slightly stronger than A1. In the remaining sections, A2 continues to develop, and A1 and the syncline S1 drop down the left-hand flank of A2, losing strength as they go, until (section A–A) the fold A1–S1 has died out, leaving A2 to continue as the right-hand *en echelon* repetition of A1.

[1] The behavior of a fold can conveniently be represented by plotting, in plan and longitudinal projection, the traces of the intersections of a bed surface with the axial planes.

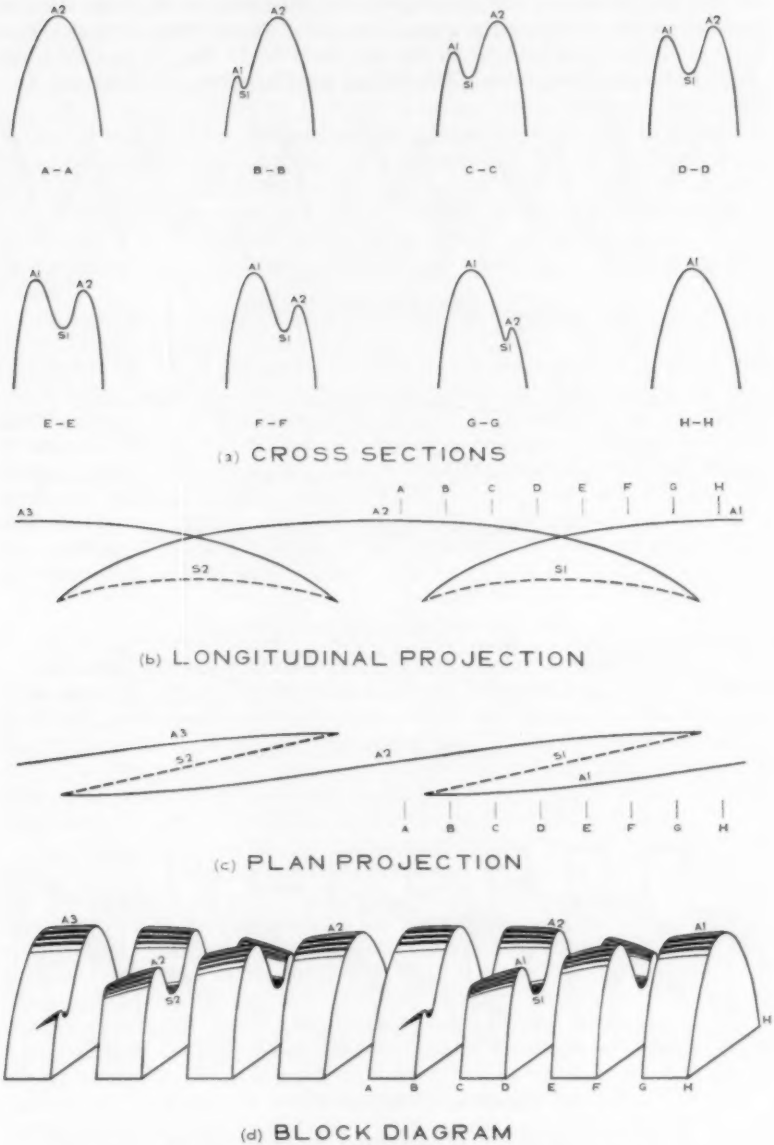
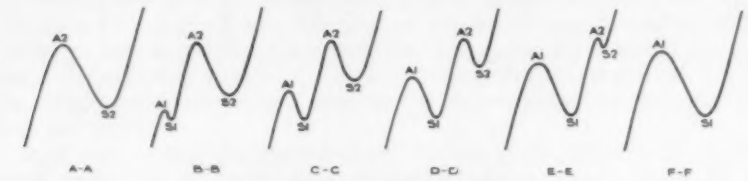


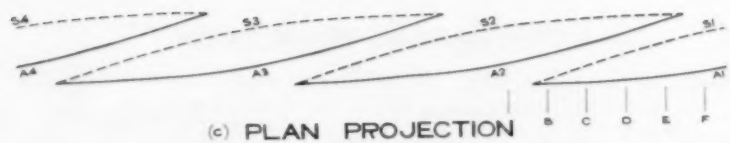
FIG. 2. A zig-zag pattern of right-hand *en echelon* folding.

The basic feature is that the outgoing and the incoming anticlines dive, one past the other, on opposed plunges (Fig. 2b). In so doing, they develop a local or linking syncline (S1 in the case illustrated) that exists only in the area of changing fold shape. The linking syncline must, of a necessity, have

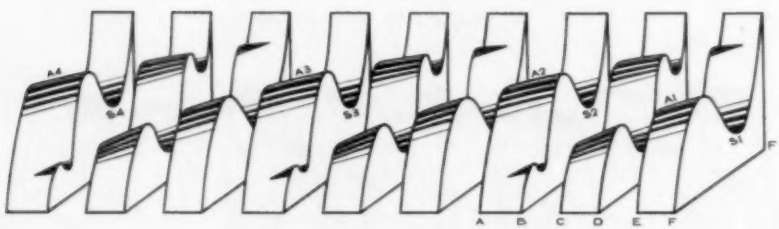


(a) CROSS SECTIONS

(b) LONGITUDINAL PROJECTION



(c) PLAN PROJECTION



(d) BLOCK DIAGRAM

FIG. 3. An elliptical pattern of right-hand *en echelon* folding. The individual folds plunge to the left across the overall horizontal plunge of the fold series, and have in plan view a trend which is oblique to the overall strike of the fold system.

a plunge intermediate between those of the two anticlines. The axes of the linking syncline and the two anticlines form a characteristic zig-zag pattern in plan view (Fig. 2c).

Elliptical Pattern.—This more complex form is developed where both an anticline and a syncline are involved in an *en echelon* change. The main features of this type for a right-hand *en echelon* are presented in Figure 3. The original fold A1–S1 is shown in cross-section F–F. In section E–E, a new fold A2–S2 forms on the right-hand flank of S1. In sections D–D and C–C, A2–S2 gains strength and A1–S1 declines in size. In section B–B it has become a minor fold on the left-hand flank of A2, and in section A–A, A2–S2 emerges as the right-hand *en echelon* repetition of the original fold A1–S1.

The fold plunge relationships involved in this change are shown in Figure 3b, and the right-hand offsets between the individual folds are shown in Figure 3c. A clearer picture is presented by the block diagram in Figure 3d and it is noticeable here that, although the individual folds trend to the left, the overall plunge of the folding is horizontal, i.e., a line joining the centers of folds A1–S1, A2–S2, A3–S3 and A4–S4 is horizontal. The pointed "elliptical" outlines formed by the pairs of anticlines and synclines are characteristic for both the plan and longitudinal views (Figs. 3b, 3c). In contrast with the zig-zag pattern, each fold forms a self-contained unit which starts from nothing, reaches a maximum, and then dies out. There is no direct interference of one fold with another.

EXAMPLES OF *EN ECHELON* FOLDING

Burbanks.—In the Birthday Gift mine at Burbanks, which is about five miles south of Coolgardie, Western Australia, thin gold-quartz reefs follow a weak tuff band interbedded with Precambrian basaltic lavas. The rocks are highly folded along north-easterly striking axes (which will be described as north) to give, in the mine area, a west-limb fold plunging gently north. In most parts of the mine, the height of this fold, from the keel of the Birthday syncline to the crest of the Birthday anticline, is about 400 to 500 feet.

Figure 4 gives a portion of the interpretation of the fold pattern of the mine, covering a right-hand *en echelon* break of the zig-zag type in the Birthday anticline from A1 to A5. An intermediate anticline A2 and two linking synclines S2 and S5 are involved in the change. In the cross section at D–D, a new fold A2–S2 is forming on the east flank of the main anticline A1. One hundred feet farther north (section C–C) A1 is still the main anticline but S2 has deepened considerably. A1 has, however, developed a very steep plunge, so that A1 and S2 meet about 40 feet north of the section, to cancel one another out. For a short distance A2 is the main anticline, but fold A5–S5 sweeps in from the right hand flank, climbs rapidly, and becomes the main anticline on section B–B, with a new combination A2–S5 forming a smaller fold on its left-hand flank. Further north again (section A–A) A2 and S5 cancel out, leaving A5 to continue as the right-hand *en echelon* repetition of fold A1.

These variations in fold plunge are traced in detail in the longitudinal projection, and a course that can be followed along the succession of anticlinal crests and synclinal keels from A1 to A5, is indicated by arrows. The plan relationships of these folds and the right-hand offset are indicated in Figure 4 in the plan of No. 2 Level, where the plunge directions of the anticlines are indicated by arrows. It is noticeable here that the syncline S2 causes a complete break in the continuity of the bed at this level.

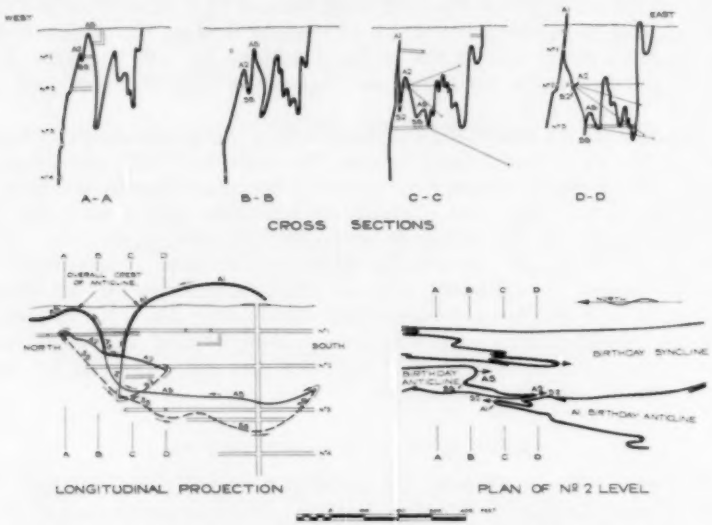


FIG. 4. Birthday Gift Mine, Burbanks, Western Australia. Plan, cross sections and longitudinal projection of part of the mine, illustrating a right-hand *en echelon* interruption of the zig-zag type in the Birthday anticline.

As can be seen from the longitudinal projection the changes in fold plunge are considerable. Locally, there is a difference of about 150° between A1 and A5 but, since A1 dives past one side of A2, and A5 rises rapidly on the other, it is not necessary to "break the back" of the anticline to achieve this severe "cross-fold." The adjustments needed are readily made by the easier process of shearing and rock flowage in the flanks of the folds.

The Birthday anticline has been traced in detail over a length of nearly 4,000 feet. In the area illustrated in Figure 4, as in other sections of the mine, varying plunges both north and south are present, ranging from horizontal to nearly vertical. The overall plunge of the folding is flat, and so there is a preponderance of flat plunges, but there are so many other angles present that a clear picture emerges only when the fold pattern is worked out over a considerable distance along the strike. Some caution is needed, therefore, in applying the maxim that the smaller folds indicate the plunge of the major features.

Rock Specimen.—Figure 5 is a photograph showing portion of an *en echelon* fold pattern of elliptical form, in a specimen of banded iron formation collected from Precambrian greenstones at Evanston, Western Australia. Fold A2 is the *en echelon* repetition of A1 but the change is not perfect in form, as the two folds are connected by a shelf that carries a series of minute fold wrinkles. Folds A3 and A4 are of perfect form, with an element of over-lap

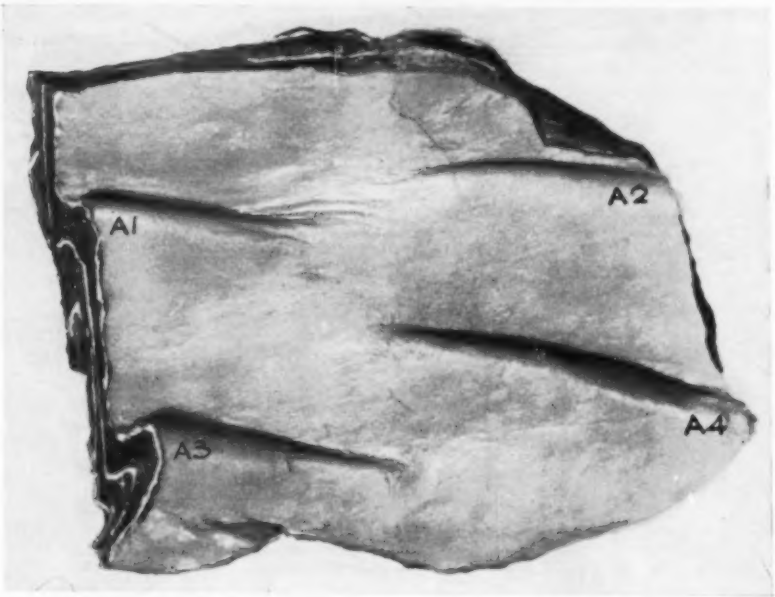


FIG. 5. An elliptical pattern of *en echelon* folding in banded iron formation, Evanston, Western Australia. The specimen is approximately 11″ long, 10″ high and 2½″ thick. It shows two *en echelon* pairs, A1–A2 and A3–A4. The overall plunge of folding is from A2 to A1 or from A4 to A3.

between them. The *en echelon* repetition in this specimen is left-hand. As photographed, the plunge of the individual folds is to the right but the overall plunge of folding is to the left.

Kalgoorlie.—The main features of Kalgoorlie geology are shown by the surface plan and two cross sections given in Figure 5A. The core of the structure is the deep and tight Kalgoorlie syncline that divides the orebodies of the field into the Eastern and Western Lode Systems. On the eastern side of the field (between the Kalgoorlie syncline and the Kalgoorlie anticline), mining operations have exposed the quartz-dolerite calc-schist contact over a considerable area, thus revealing its folded structure. Contours of this contact are given in Figure 6a. These gloss over many features of a complex and

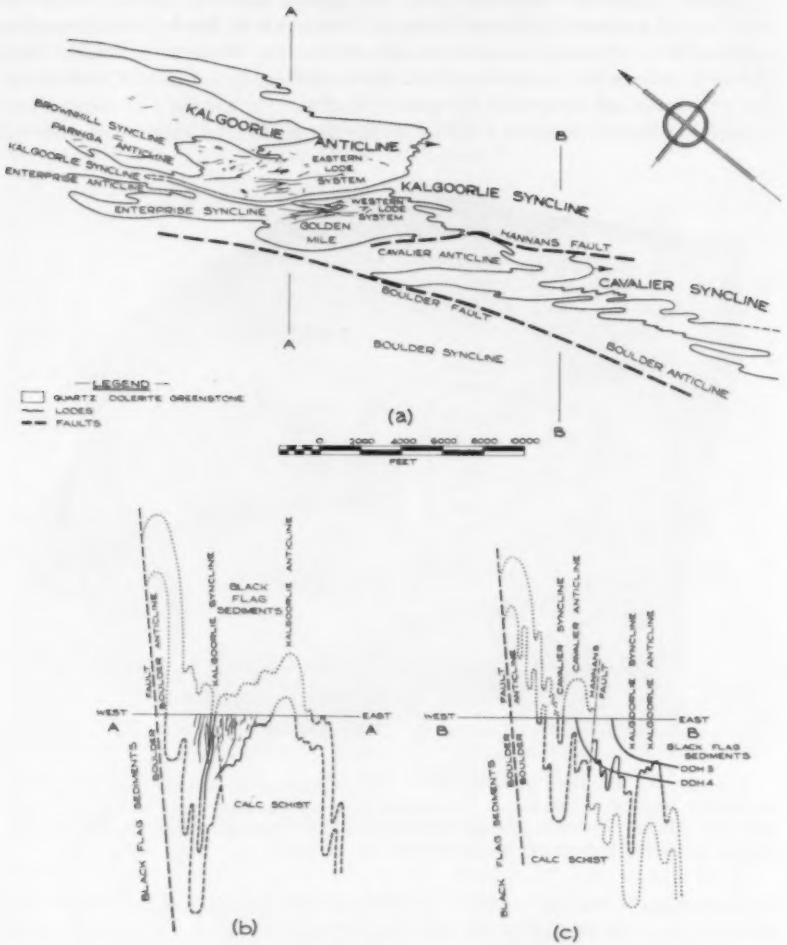


FIG. 5A. Kalgoorlie, Western Australia. (a) Plan showing surface geology. (b) and (c) Cross sections, looking north, along lines A–A and B–B of Figure 5a. In Figure 5a, the unshaded area to the east of the quartz dolerite greenstone is occupied by Black Flag sediments. The cores of the Kalgoorlie, Cavalier, and Boulder anticlines are occupied by calc-schist (highly carbonatised basaltic lavas). Black Flag sediments lie to the west of the Boulder fault. In the two cross-sections, rocks other than quartz dolerite greenstone are named at their various points of occurrence.

inter-related fold and fault pattern but, even so, they present a picture that is representative of the main features of the folding of this portion of the field.

It is noticeable in the diagram that the near-surface contour (+1,000 ft.) shows a strongly folded shape; that there is a weakening of this fold at +500 feet; and that the 00 contour is almost straight. These changes are due to the dying out, southwards and in depth, of the fold Paringa anticline-Brown Hill syncline. This fold is replaced by a new but weaker combination, Lake View anticline-Australia syncline, which builds up at a deeper position to the south and west of the dying fold. This is a right-hand *en echelon* repetition of elliptical form that had a marked influence on ore occurrence. A minor feature is that the Brownhill syncline shows a zig-zag change superimposed on the larger elliptical pattern.

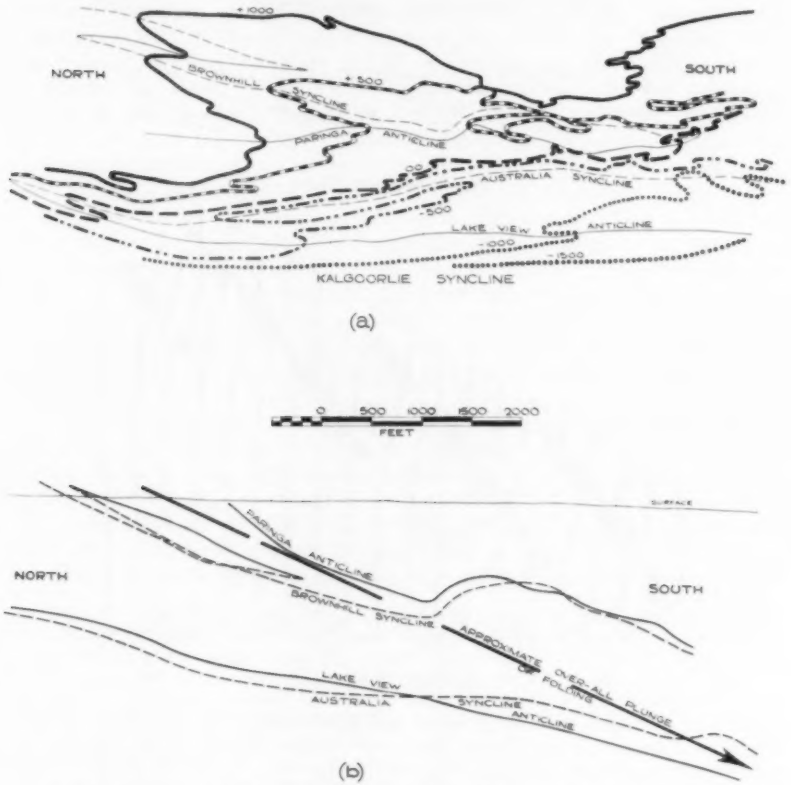


FIG. 6. Kalgoorlie, Western Australia. (a) Contours of the quartz dolerite-calc schist contact, where exposed by the workings on the eastern side of the field. Contour datum—sea level. (b) Longitudinal projection showing the plunge lines of the main folds. The overall plunge of the fold system is indicated by an arrow.

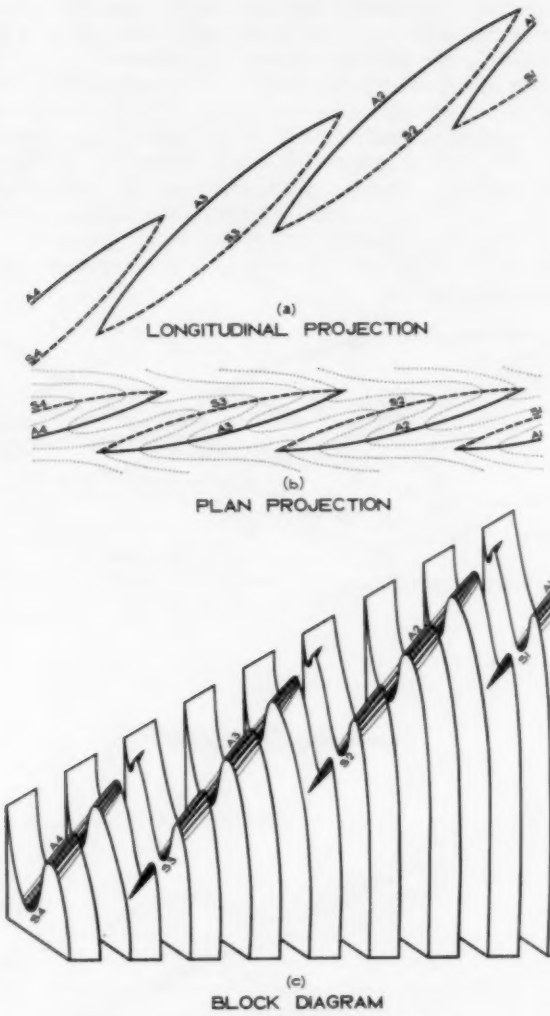


FIG. 7. Plunge relationships for a right-hand elliptical *en echelon* in a right-hand fold shape. In Figure 7b, the dotted lines are contours of the bed surface and indicate the right-hand shapes of the individual folds. In Figure 7c, the overall trend of the fold system, for both strike and plunge, is parallel to a line joining the truncated tops of the individual blocks of the diagram.

The longitudinal view given in Figure 6b shows the plunges of the folds to be very flat to the south. Joining the estimated centers of the two folds gives, however, a steeper angle of about 24° south. This is the approximate over-all plunge of the folding. A check on this figure is obtained by the position of quartz dolerite at the crest of the Kalgoorlie anticline given by D.D.H. 3 (see cross-section B–B in Fig. 5). This intersection is about 7,000 feet south of the surface outcrop of the corresponding position (Fig. 5a), and the two observations give the Kalgoorlie anticline an average plunge of 17° south.

PLUNGE RELATIONSHIPS IN ELLIPTICAL PATTERNS OF *EN ECHELON* FOLDING

In the theoretical illustrations given to date, the overall plunge of folding has been horizontal in each case. In Figure 7 the elliptical series of Figure 3 has been tilted 30° to the left, so that, in longitudinal view (Fig. 7a), each successive fold, going down the plunge, is in a position above the preceding member of the series. The overall plunge of the series is 30° but locally the plunges of the constituent folds range from 30° to 55° and average 40°. As can be seen from Figure 7b the tilting of the fold system does not affect the right-handed relationship between the various folds and it can be seen, from the contours of the bed surface, that the fold shape is right-hand. The picture is one, therefore, of right-hand *en echelon* in right-hand folding in which the plunges of the individual folds are steeper than the overall plunge of folding.

If the same fold series is tilted 30° to the right, the *en echelon* remains right-hand (Fig. 8b) but the fold shape becomes left-hand (see contours). In longitudinal view (Fig. 8a), each successive fold (down the plunge direction) is lower in position than its predecessor, so that the overall plunge of 30° is steeper than the average plunge of 20° of the individual folds. Local plunges range from 5° to 30°.

Two further cases can be illustrated by viewing mirror images of the diagrams, or, perhaps more conveniently, by viewing them back-to-front against the light. Figure 7 becomes left-hand *en echelon* in left-hand folding, with the plunges of the individual folds steeper than the overall plunge; Figure 8 becomes left-hand *en echelon* in right-hand folding and the plunges of the individual folds are flatter than the overall plunge.

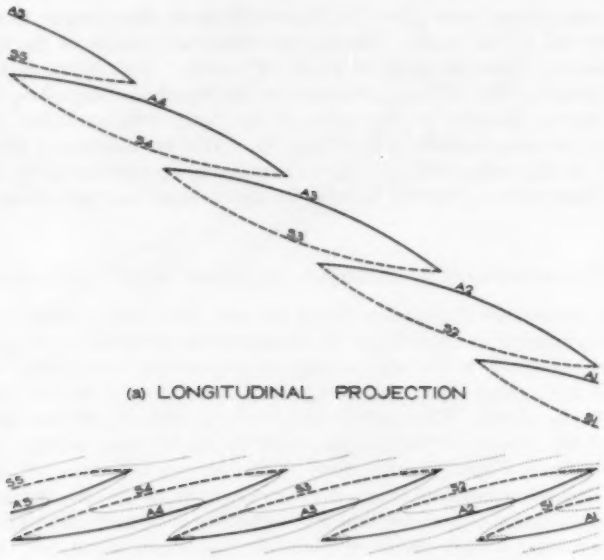
From these observations, a rule for elliptical series can be formulated:

Where left-hand *en echelon* is developed in a left-hand fold shape or where right-hand *en echelon* is developed in a right-hand fold shape, the plunges of the individual folds are steeper than the overall plunge of the *en echelon* series; where left-hand *en echelon* occurs in a right-hand fold shape or where right-hand *en echelon* occurs in a left-hand fold shape, the plunges of the individuals are flatter than the overall plunge of the folding.

Or, more concisely:

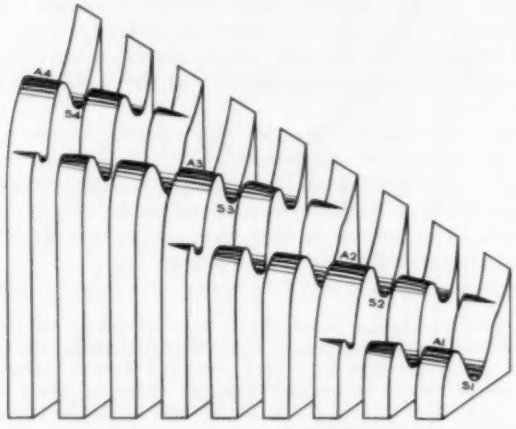
Left-hand, right-hand
Right-hand, left-hand } Individuals are steeper.

Left-hand, left-hand
Right-hand, right-hand } Individuals are flatter.



(a) LONGITUDINAL PROJECTION

(b) PLAN PROJECTION



(c) BLOCK DIAGRAM

FIG. 8. Plunge relationships for a right-hand elliptical pattern in a left-hand fold shape. In Figure 8b, the dotted lines are contours of the bed surface and indicate the left-hand shapes of the individual folds. In Figure 8c, the overall trend of the fold system, for both strike and plunge, is parallel to a line joining the truncated tops of the individual blocks of the diagram. Compare plunge relationship with that of Figure 6b.

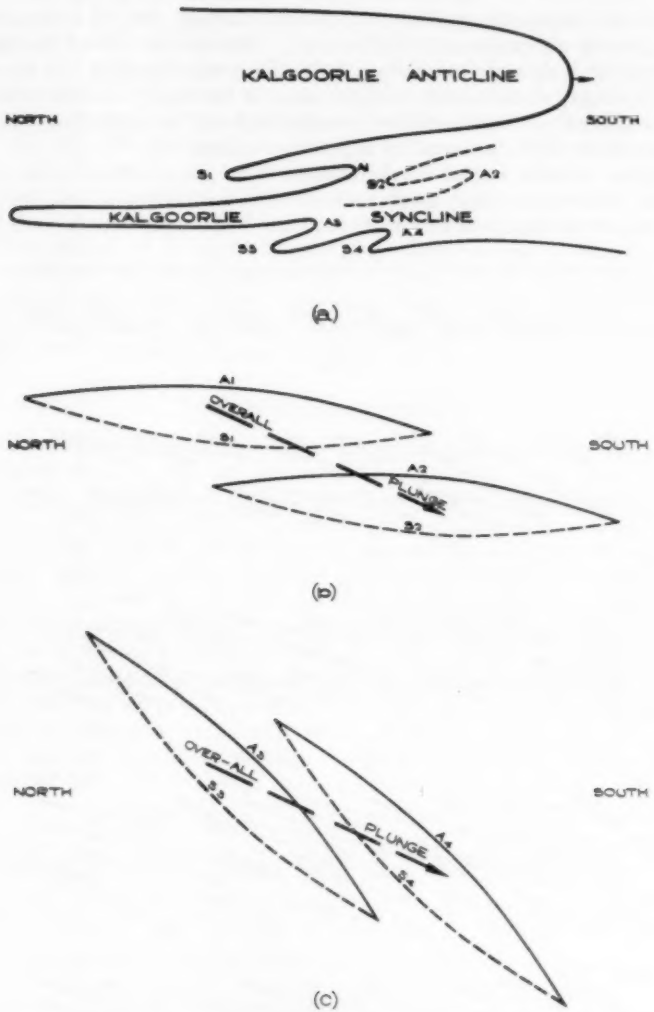


FIG. 9. Diagrammatic explanation of plunge relationships between the eastern and western sides of the Kalgoorlie field. (a) Diagrammatic sketch plan of the quartz dolerite-calc schist contact. (b) Sketch longitudinal projection of fold plunge on the eastern side of the field. (c) Sketch longitudinal projection of the probable fold plunge relationships on the western side of the field.

These ideas offer an explanation of a divergence in fold plunge that can be seen in the Kalgoorlie goldfield. A general surface plan of Kalgoorlie has been given in an earlier section (Fig. 5a). The eastern side of the field lies between the Kalgoorlie anticline and the Kalgoorlie syncline and so, as the folding plunges to the south, the fold shape is left-hand. As has been indicated in Figure 6, the *en echelon* is right-hand and the individual folds have plunges flatter than the overall plunge of the folding.

On the western side of the field (west of the Kalgoorlie syncline in Fig. 5a) the fold shape is right-hand, but no direct observations of fold plunge can be made, as mining operations have not gone deep enough on this side of the

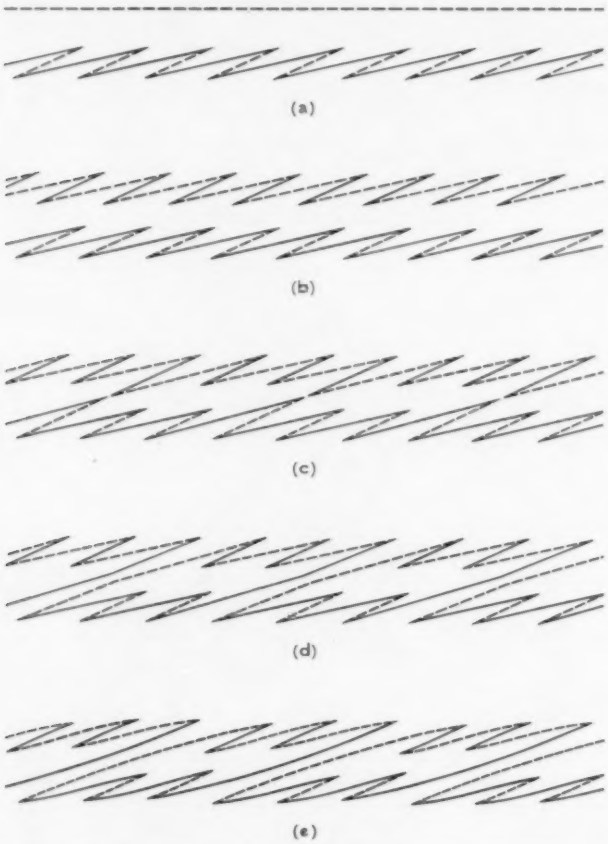


FIG. 10. Sketch plans showing how the merging together of two right-hand zig-zag systems will produce a series of elliptical folds combined with subordinate zig-zag folds. Anticlines are shown as full lines and synclines as dashed lines.

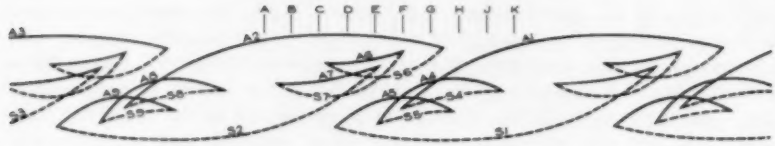
field to expose the quartz dolerite-calc schist contact. However, sufficient is known to indicate a fold plunge of at least 40° S and possibly steeper. An explanation for this divergence in plunge is given in Figure 9. Figure 9a is a diagrammatic sketch plan of the shape of the quartz dolerite-calc schist contact. A1 corresponds to the Paringa anticline and S1 to the Brownhill syncline. A2 and S2 represent the Lake View anticline and the Australia syncline, and the fold is shown as a dashed line to indicate that it occurs at a lower level than A1–S1. A3–S3 and A4–S4 are hypothetical folds forming an *en echelon* pair on the western side of the Kalgoorlie syncline. Folds A1–S1 and A2–S2 are of left-hand shape and, as they combine to form a right-hand *en echelon*, their plunge relationship will be as is indicated in Figure 9b. Folds A3–S3 and A4–S4 are of right-hand shape and, for a right-hand *en echelon*, would have steep plunges, as in Figure 9c. The overall plunge of folding is at the same angle for each of the two series.

COMBINATIONS OF TYPES

The illustration given in Figure 2 of the zig-zag type of *en echelon* pattern pre-supposes that, on one side or other of the anticline, there is a syncline that does not enter into the *en echelon* changes (Fig. 10a). It is possible, of course, for this syncline to have an *en echelon* pattern of its own, as in Figure 10b, and it is of interest then to examine the effect of allowing the two sets of folds to coalesce. In Figure 10c, the individual folds have been brought into line with one another, and the size of every third member of the two sets has been increased to the point where the fold tips are just touching. If their size is further increased, as in Figure 10d, a new combination of folds is produced. This is sketched in more conventional form in Figure 10e, where it can be seen that the groups of three have coalesced into an elliptical pattern on which is superimposed a lesser series of zig-zag folds. For the main syncline, the zig-zags lie in the upper right-hand quadrant of the ellipse, whereas, for the main anticline, they are restricted to the lower left-hand

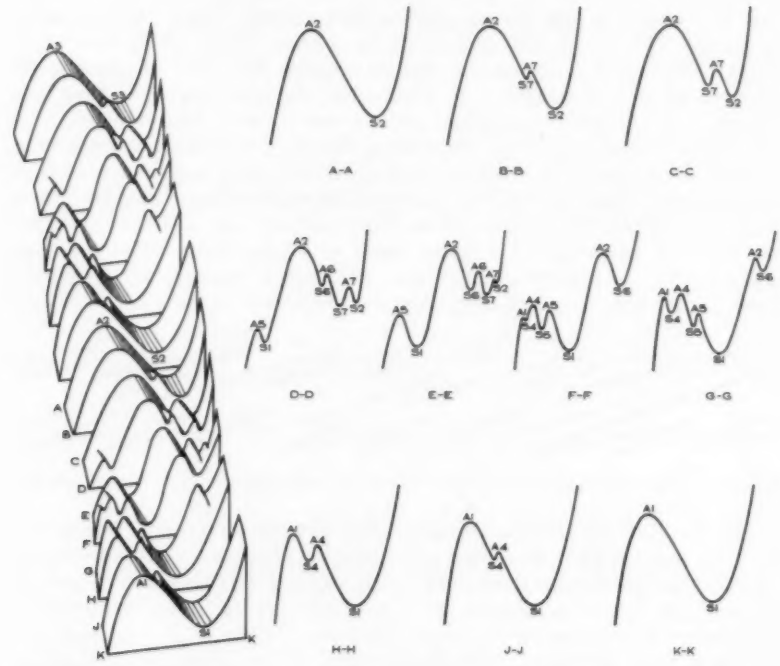
FIG. 11. Sketch plan of a combined elliptical zig-zag series for left-hand *en echelon*.

quadrant. Such an arrangement is inherent in getting right-hand zig-zags to fit easily and naturally into the axial pattern of a larger right-hand elliptical series. The subordinate position of the zig-zag type in a combined *en echelon* pattern is thought to arise from the limitation of any one series of zig-zags to interference in only one of the major fold axes. Figure 11 is complementary to Figure 10e, and shows a left-hand pattern in which the zig-zags are restricted to the upper left and lower right quadrants. These two diagrams are believed to be basic patterns for the combined type. They can be matched by



(a) LONGITUDINAL PROJECTION

(b) PLAN PROJECTION



(d) BLOCK DIAGRAM

(c) CROSS SECTIONS

FIG. 12.

two more diagrams in which the main anticline lies on the upper side of the ellipse and the main syncline on the lower side.

Combined forms could, of course, be more complex than is indicated in Figures 10e and 11. Lesser zig-zags could, for instance, occur within the structure of the zig-zags that embroider the main elliptical folds of the series. In addition, smaller scale elliptical patterns could occur as minor features, but they would have to lie on the flanks of other folds, which could be either elliptical or zig-zag in type. In turn, these minor elliptical series could have lesser zig-zags within their axial patterns, and so on. It is of more interest, however, to view this picture from the small scale towards the larger. The smallest drag-folds could have an *en echelon* arrangement which could integrate to a larger pattern at the minor fold level; these minor folds could in turn build up to a larger *en echelon* series, and so on, extending ultimately to an *en echelon* pattern in the major fold structure of a district.

Returning to idealized patterns, the case of Figure 10e has been worked out in detail in Figure 12. A1 is broken up by new folds (sections J–J to G–G) and, as a complex feature, becomes progressively smaller in each succeeding section. After section F–F, only the main syncline S1 and one of the minor anticlines A5 are left; these fade out beyond section D–D. A new anticline A2 forms on the right-hand flank of S1 in section G–G, and brings with it a series of minor folds that develop into a complex syncline in sections E–E and D–D. The new main syncline S2 is a minor feature on the right-hand side in these two sections. The complexity of the syncline decreases in sections C–C and B–B, and a single strong fold A2–S2 emerges in section A–A as the right-hand *en echelon* repetition of the original fold A1–S1. The right hand off-set is seen best in the block diagram in Figure 12. The overall trend of the fold system is from A1, to A2, to A3, and the overall plunge of the folding is horizontal.

In this, as in earlier illustrations of the elliptical pattern, there is no overlap of the plunge lines of successive folds, the purpose being to preserve clarity of illustration. Figure 13 repeats the block diagram of Figure 12 but with the plunge lines brought to approximately the same level in the areas where the folds overlap one another. It is noticeable here that the strong fold A1–S1 of section K–K disintegrates in a short distance into a characterless series of smaller folds of more or less equal height (sections F–F and E–E), and that, in a surprisingly short distance, a strong new fold emerges from the right-hand side (A2–S2 of section A–A). The rapid decline of one fold system and the equally rapid emergency of a new system seems characteristic of complex *en echelon* folding.

FIG. 12. A combined pattern, showing a right-hand elliptical series in which the axes are interrupted by subordinate zig-zags. The individual folds plunge to the left but the overall plunge of the fold series is horizontal. In plan view, the overall trend of the fold system is parallel to the right-hand side of the block diagram.

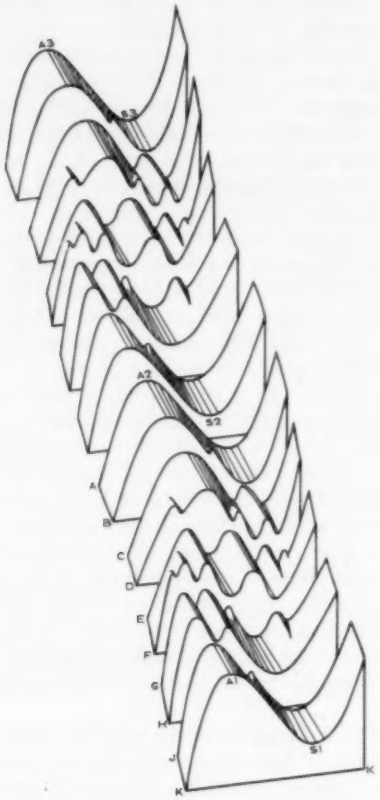


FIG. 13. The block diagram of Figure 12 redrawn with the plunge lines of the folds brought to approximately the same level in the areas of over-lap.

EXAMPLES OF COMPLEX *EN ECHELON* FOLDING

Bullfinch.—The Copperhead mine at Bullfinch, Western Australia, lies on the eastern flank of a steeply dipping isoclinal syncline of a width of two to four miles, and a length of some forty miles or more (*2*). This syncline has formed in Precambrian greenstones that are flanked on either side by major anticlinal areas of concordant granite. The greenstone belt is strongly folded throughout its length.

The main host for the gold orebodies of the district is a banded tuffaceous greenstone of a thickness of 1,000 feet or more that is interbedded with basaltic lavas, ultrabasic rocks, amphibolites, and a considerable thickness of

overlying sediments. At the Copperhead mine, bedded lodes occur in two positions within the banded greenstone—an upper lode in a dolomitized band of well bedded greenstone (Northern Series), and a lower position in mineralized slates (Southern Series). The present concern is with *en echelon* effects in the fold structure of the Northern Series. Similar and sympathetic effects are found in the Southern Series but they are not known in any great detail.

A composite plan of the Northern Series at 400 feet vertical intervals is given in Figure 14. The folding plunges to the north at about 40° and the individual folds are strongly over-turned, as is evident in the cross sections A–A and B–B. In some areas, minor fold axes are strongly collapsed and distorted. Despite these complexities, there can be seen in Figure 14 the elements of an *en echelon* change in the main syncline. It is V-shaped on the surface and at No. 4 Level, but has become U-shaped at No. 8 Level, due to the development of a new syncline S3. Below No. 8 Level, S3 gains in strength and S2 drifts to the right so that, at No. 12 Level, S3 has become the main syncline and S2 has weakened to a minor strike bend on the right-hand flank of S3. In consequence, the main syncline has returned to a V-shape. This is a left-hand *en echelon* pattern in which there is a minor change from S1 on the surface to S2 at No. 4 Level, and a major break from S2 at No. 4 Level to S3 at No. 12 and deeper levels.

This *en echelon* effect in the syncline has been accompanied by major changes in the anticline. From the surface to No. 6 Level, the western flank of the main syncline is made up of a series of inconspicuous folds that lead to an ill-defined anticline—point A. At No. 7 Level, major changes commence and a more definite but bifurcated anticline emerges at No. 8 Level. This anticline gains in strength with each succeeding level down to No. 16, where the overall trend of the limb between it and the main syncline is nearly at a right-angle to its counterpart on No. 4 Level.

A close parallel can be seen between these changes and those indicated in Figure 13, if due allowance is made for right-hand *en echelons* in Figure 13 instead of left-hand, and also if the cross-sections of the diagram are regarded as being equivalent to the plan views of the Copperhead mine. Thus, section H–H of Figure 13 is generally similar to the Copperhead surface, and sections F–F and E–E give a fair representation of the area between No. 4 and No. 6 Levels; section D–D would correspond approximately to No. 8 Level and Section A–A would represent the emergence of a single strong fold in the deeper levels of the mine. It is interesting to observe that the overall trend of the series of minor folds in sections F–F and E–E is nearly horizontal, giving a marked contrast to the steeply dipping right-hand flank of fold A2 in section A–A.

Ore occurrence at the Copperhead Mine seems to have arisen from a final shiver of stress that caused a tensional fracturing of the previously folded and dolomitized host-rock. The fractures were invaded by mineralized quartz veins of a thickness of a few inches to several feet, and these auriferous veins show the inter-lacing and anastomosing tendencies common to tension vein systems. Because of this, the behavior of the ore shoots is somewhat erratic

in detail but, nevertheless, they show a good general agreement with fold structure.

Unfortunately, the severe overturning of the folding, which is evident in the cross-sections in Figure 14, precludes a simple presentation of the ore

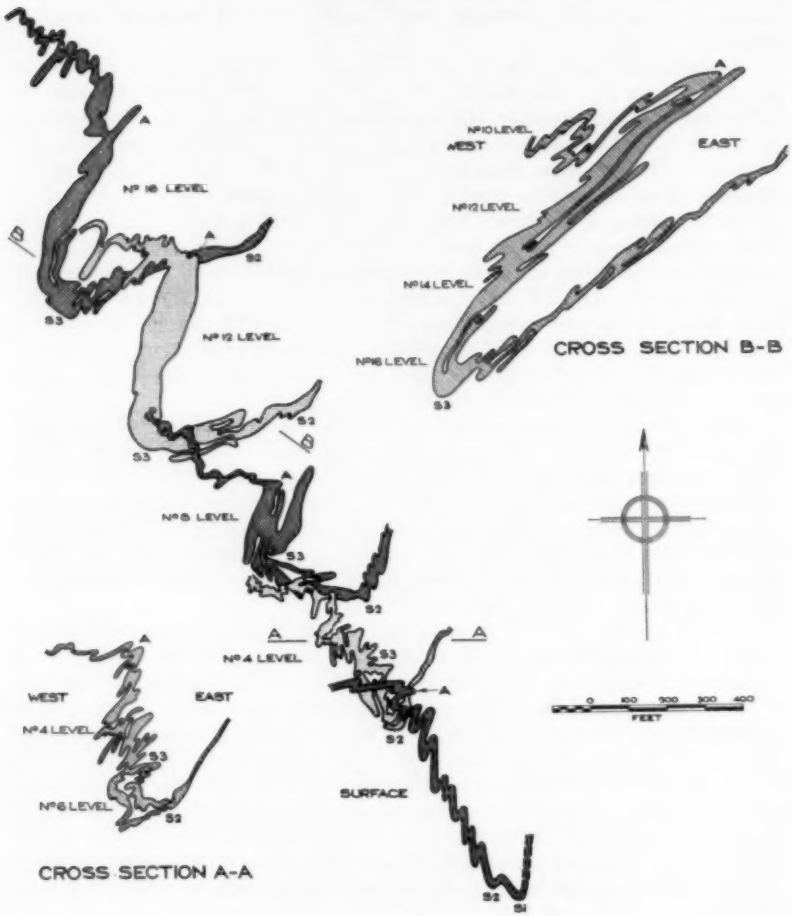


FIG. 14. Copperhead Mine, Bullfinch, Western Australia. Composite plan of the Northern Series from the surface to No. 16 Level showing the fold structure of the dolomitized lode bed, with cross sections along lines A–A and B–B. In cross section B–B, a somewhat "free" interpretation has been made of lenses of greenstone lying within the dolomite, to indicate the probable nature of the fold structure. More generalized outlines are given in the composite plan, particularly for levels below No. 8.

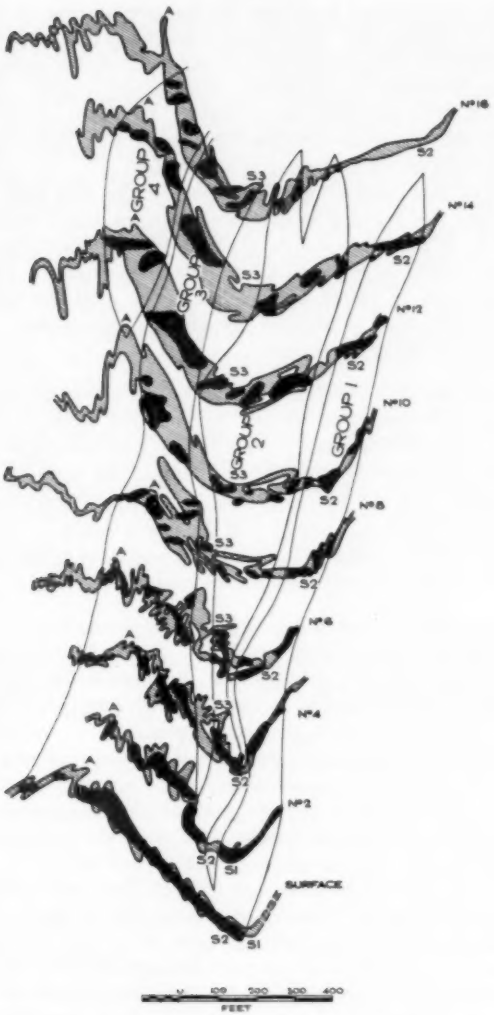


FIG. 15. Copperhead Mine, Bullfinch, Western Australia. Diagrammatic composite plan of the Northern Series from the surface to No. 16 Level, showing the relationship between ore occurrence and fold structure. The dolomitized lode bed is shaded and is shown in more detail above No. 8 Level than below. Ore shoots are colored black. They have been linked together into four main groups. The main syncline is S1–S2 on the surface and No. 2 Level, S2 on No. 4 and No. 6 Levels, S2–S3 on No. 8 and No. 10 Levels, and S3 on the three deepest levels.

pattern. This position has been met by the preparation of a diagrammatic composite plan—Figure 15. To produce this diagram, the first step was to rotate the limbs of the main syncline outwards, using for each main level the degree of rotation needed to produce a satisfactory result. These distorted level plans were then arranged, at a slightly increased north-south spacing, in such a way that the main syncline runs straight up the center of the diagram, in contrast to its oblique trend in Figure 14.

The effect of this construction is to remove the over-turn of the folding while preserving the relative positions of various main features from one level to the next. The clearer view given by this method allows the various ore shoots to be linked, in Figure 15, into four main groups. These groupings are slightly arbitrary in places but are consistent with the fold pattern, and have, in the main, been confirmed by stoping operations. Study of the diagram reveals the following features:

Group 1 marches with syncline S2, and the ore-shoots peter out below No. 14 Level where the parent syncline has become very weak.

Group 2 lies mostly to the east of syncline S3 and the ore-shoots weaken on No. 16 Level in the relatively straight east limb of the main syncline.

Group 3 sits astride the main anticline in the upper levels of the mine but drifts down towards the main syncline in the lower levels.

Group 4 commences below No. 10 Level and also drifts down the anticlinal flank at each successively deeper level.

The general effect is that the groups of ore-shoots trend to the right of the overall course of the main fold structure. Group 1, and perhaps Group 2, indicate a tendency for the ore-shoots on the right-hand side to die out in depth, but this is compensated by Group 4, which suggests a replacement on the left by new shoots coming in at deeper levels.

Finally, there is some suggestion on No. 16 Level of a new fold structure developing to the west of the main anticline A.

Kalgoorlie.—Beyond the southern end of the Kalgoorlie field a deep diamond drilling test has been in progress for some years, seeking a repetition of the mineralization in an area where, if it exists, it would be concealed by a higher member of the rock sequence, the Black Flag sediments. The initial project aimed at following southwards along the projected trend of the Kalgoorlie syncline, which is clearly the core of the known productive area. However, the results of this work showed that the problem is more complex than had been pictured originally. The key data are shown in the cross sections given in Figure 5.[2] In cross-section A–A, the Kalgoorlie fold is strong and well-defined but, in cross-section B–B the drilling reveals that it has shrunk considerably in size. This decline in the Kalgoorlie fold is

[2] The original view of the structure was given in the "Geology of Australian Ore Deposits," A.I.M.M. 1953, p. 79–93, "The Structure of the Kalgoorlie Goldfield," by J. D. Campbell. Subsequently, the first 2,000 feet of D.D.H.4 (see section B-B in Figure 5 of the present paper) revealed quartz dolerite in an area covered by salt-lake deposits and led to the recognition of the previously unknown Cavalier anticline and syncline.

compensated by the development of the Cavalier fold, which is not known at the position of section A–A and, if present there, is probably very weak.

The possible significance of these changes in the fold pattern can be assessed by analogy with the block diagram of Figure 12—if allowance is made for the folds in Figure 12 being on the left instead of on the right side of a major anticline. Thus, the cross-section A–A of Figure 5 is roughly equivalent to section K–K of the diagram, and Kalgoorlie section B–B shows a breaking up and degeneration of the folds similar to that of sections F–F and E–E in Figure 12. If the analogy is pursued further, it can be seen that the fold pattern of the Kalgoorlie area could be a right-hand *en echelon* on a major scale, with fold A1–S1 of Figure 12 being equivalent to the Kalgoorlie fold, and fold A2–S2 representing the Cavalier folding. On this view, the surface position of the Cavalier fold structure (i.e., the general environs of section B–B in Fig. 5a) would lie in the area where it is developing at the expense of the Kalgoorlie fold. The maximum development of the Cavalier folding would then be further to the south, and would lie therefore in an area where the south plunge of the folding carries the quartz dolerite below the Black Flag sediments. The disclosure of these new features has led to the drilling test being shifted westwards onto the Cavalier position and it is now following the Cavalier syncline southwards, seeking an area where the fold structure has built up again to a strength sufficient to give the conditions necessary for the occurrence of ore-bodies.

CONCLUSIONS

The illustrations given in this paper indicate that the widely accepted rule, that the minor fold indicates the axial trend and fold plunge of the larger structure, is subject to reservations which, in cases of severe folding, can amount to an almost complete rejection. A supplementary and, in some cases, alternative rule would be that the minor *en echelon* is indicative of the nature of the larger *en echelon* structure of which it forms a part. This is, in fact, inherent in the analysis of Tokuda's experiment given at the beginning of this paper. The stresses must be of constant orientation throughout the right-hand half of Figure 1a—an anti-clockwise system yielding a left-hand pattern of *en echelon* folding. In the left-hand half of the figure the stress system would be clockwise, and it is interesting to note, in other photographs of Tokuda's experiments, that this side shows a right-hand *en echelon*. A constant direction of *en echelon* offset for any particular area is in accord with the writer's observations at Kalgoorlie, Coolgardie, Bullfinch, and elsewhere in Australia.

The *en echelon* view of folding suggests, as at Burbanks (Fig. 4), that a "cross-fold" is likely to be a part of an *en echelon* structure in which there are folds of opposed plunge. If the offset between these folds can be determined, it can be a guide to the nature of the larger *en echelon* structure.

It is characteristic of *en echelon* folding that the major features trend obliquely across the minor folds, which are their constituent parts. However, the geologist sees and maps only the lesser folds and his problem is to see

the larger picture. The *en echelon* nature of the folding and its habit may be easy to determine as at Burbanks, but mostly, as at Kalgoorlie and Bullfinch, an extensive three-dimensional knowledge is needed before the existence and characteristics of an *en echelon* pattern can be recognized.

Where recognizable, the diagnostic features of *en echelon* folding can give important clues in the search for ore extensions and ore repetitions in areas where fold structure is a major influence, either directly or indirectly, in the occurrence and location of ore-bodies. For instance, in the important old gold-field at Stawell, Victoria, the flatly north-plunging system of ore bodies follows a minor fold of right-hand shape that lies to the west of the main anticline of the area and trends to the left of the larger fold, thus giving a clear suggestion of a right-hand *en echelon* (1). A close analogy is given by Figure 7, where fold A2–S2 could be taken as representing the minor fold carrying the known ore-bodies and fold A3–S3 could be regarded as its possible *en echelon* repetition. The old workings followed down the outcropping fold and prospected its weakening continuation, without success, for a considerable distance ahead of the ore limit. If the view is correct that there is a right-hand *en echelon* in a right-hand fold shape, the prospect for an ore repetition would lie to the right and north of the old workings at a comparatively shallow level, rather than in the more obvious position covered by the old workings.

In some cases, a full knowledge of an *en echelon* structure could give surprising results, as is indicated in the rock specimen in Figure 5. If this is viewed as representing a large structure, pre-knowledge of the *en echelon* pattern indicates that a repetitive position (A3) lies to the left of and deeper than its partner (A4), despite the fact that all observed fold plunges are to the right.

ACKNOWLEDGMENTS

The necessity for an understanding of *en echelon* folding arose during the writer's work for his employers, Western Mining Corporation Limited, and he is indebted to them for the opportunities and encouragement given him, and for permission to publish this material.

He is also under a considerable obligation to Messrs. Wilfred Keddy and Ian Veale, who exercised much patience and ingenuity in the preparation of the text figures.

KALGOORLIE,
WESTERN AUSTRALIA,
August 20, 1957

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Economic Geology
Vol. 53, 1958, pp. 473–480

CHEMICAL ANALYSES OF THE FLUID INCLUSIONS IN A GROUP OF NEW MEXICO MINERALS[1]

L. L. AMES, JR.

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ABSTRACT

Many natural and synthetic crystals contain entrapped fluids representative of their growth medium. The following method was developed for the chemical analysis of such fluids:

1. Hand-cobbing, heavy media separation, and electrolytic cleaning to remove adsorbed surface ions.
2. Release of inclusion ions by ball-milling.
3. Separation of the inclusion ions from the ground mineral by electrodialysis.
4. Chemical analysis of the collected inclusion ions. Inclusion analyses of a suite of New Mexico minerals showed the major cations to be sodium and potassium with lesser amounts of lithium, rubidium, and cesium, and the major anions to be chloride and sulfate in an aqueous solution. A quantative determination of the above ions was made.

In the minerals from Portales, New Mexico, a correlation appears to exist between the sodium to potassium ratio and the temperature and sequence of deposition. Falling temperature is paralleled by a decreasing sodium to potassium ratio. This indicates an uninterrupted supply of mineral depositing solution over an extended time period.

Similar sodium to potassium ratios were found in two fluorite samples from similar geological environments.

INTRODUCTION

DURING the process of crystal growth many minerals trap portions of the fluid from which they grew. The trapped fluid inclusions range in size from less than one micron to several centimeters in maximum dimension, but inclusions large enough to be seen with the naked eye are comparatively rare.

[1] Extracted from a thesis submitted in partial fulfillment of the requirements for the Ph.D. degree at the University of Utah, Salt Lake City, Utah.

There are two general types of inclusions. That type of inclusion is termed "primary" which is representative of the original growth solution. "Secondary" inclusions may be formed when fracturing and recementing take place subsequent to the original growth of the crystal. Secondary inclusions can usually be distinguished from primary inclusions by the tendency of secondary inclusions to cut across several crystals in planar arrangement, while arrangements of primary inclusions are usually parallel to a growing face of the crystal. In practice, however, it is difficult to distinguish between these two inclusion types. The only satisfactory solution to this problem lies in a careful selection of samples. Crystals that have grown continuously in open spaces are certain to contain only primary inclusions.

An inclusion study of the minerals found at the Portales and Alamo mines in New Mexico was initiated in the summer of 1955. The purpose of the study was to determine the chemical nature of the mineral depositing solutions and the relationship between thermal and chemical history.

PREVIOUS WORK

The literature on fluid inclusions has been summarized by Smith (8) and the few quantative inclusion analyses are listed by Wahler (9). In view of these excellent summaries of inclusion literature already on record, no comprehensive literature review will be attempted. Only papers of immediate interest to this study will be reviewed here.

Grogan and Shrode (1) studied the aqueous inclusions in Illinois fluorite. These inclusions were reported to contain 4.5 percent by weight of salts, principally of sodium, calcium and chlorine, with lesser amounts of fluorine, sulfur, silica, magnesium, and iron or aluminum. These inclusion analyses were qualitative.

The only quantitative chemical analyses of aqueous inclusions in fluorite was done by Gushkin and Prikhid'ko (2), who reported the results of a microchemical determination of inclusion fluids from three crystal zones. The core, intermediate and peripheral inclusions contained 11.9, 9.9, and 5.7 percent by weight of dissolved salts with pH's of 7.0, 7.3, and 7.6, respectively. The core zones were found to be enriched in chlorine, while the peripheral zones were higher in carbonate or bicarbonate. The authors considered the latter enrichment to be due to the high lime environment prevalent during the growth of the peripheral zones. The crystals showed a weight loss of 0.16 percent on heating to 400 C, and an overall inclusion composition of 25.0 percent by weight sodium, 58.3 percent chlorine, 8.3 percent magnesium and 8.3 percent bicarbonate.

Head (3) was the first to note that many small cubic crystals of sodium chloride were present on fresh cleavage surfaces of galena. Newhouse (4) studied the primary inclusions of fifteen single crystals of galena and four of sphalerite. The crystals were cleaved and the salts that crystallized about the opened inclusions on the cleavage surface were identified microchemically. No potassium or magnesium salts were observed. The salts identified were sodium and calcium chlorides, with the concentration of the sodium chloride

appreciably exceeding that of the calcium chloride. The concentration of the inclusion fluid was estimated as equivalent to 12 to 25 grams of NaCl per 100 cc water.

Although Nicol (5) reported the presence of fluid inclusions in barite, no chemical identification was made of the salts precipitated from the evaporated inclusion fluids. No other reports on the fluid inclusions in barite were found in the literature.

ANALYTICAL METHOD

The analytical method used is essentially that of Roedder (6). A sample of handpicked single crystals was crushed and a kilogram sample of the minus 10 plus 48 mesh size fraction recovered. The sample was placed in a large

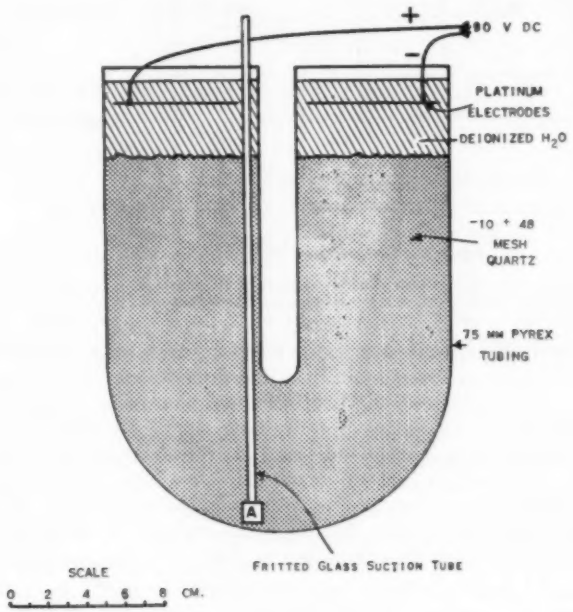

FIGURE 1. ELECTROLYTIC CLEANING CELL FOR REMOVING SURFACE IONS.

pyrex U-tube (Fig. 1), and with frequent changes of deionized water, cleaned of adsorbed surface ions. This electrolytically cleaned sample was placed in an Alundum ball mill with deionized water and ground 24 hours.

A three-compartment electrodialysis cell (Fig. 2) was used to separate the ions from the ground sample. Cathode and anode solutions were extracted at intervals and new deionized water added. Two water changes (Fig. 3) were sufficient to remove over 95 percent of the ions in the sample chamber.

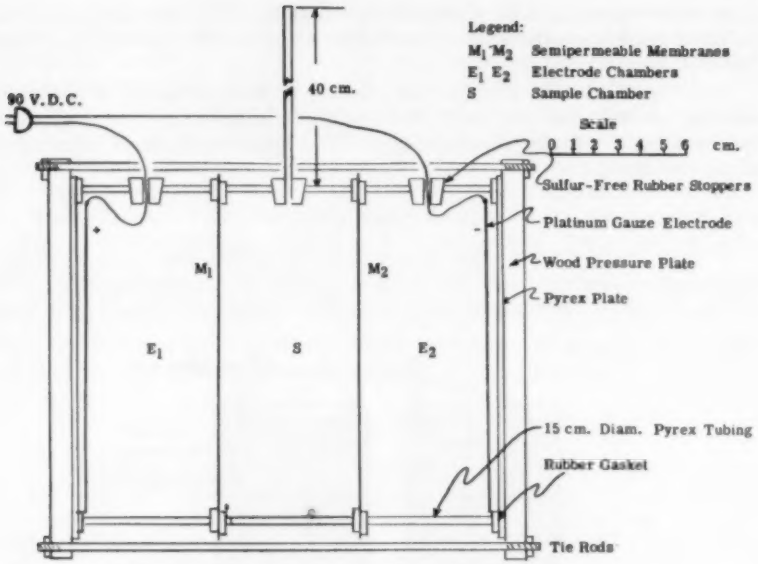

Figure 2. Electrodialysis Cell

The tube in the center cell permits the expansion of the volume of the center cell fluid by osmosis without bursting the membranes.

The respective cathode and anode solutions were then combined. After removal of calcium and aluminum from the cathode solution, an analysis was made for sodium, potassium, lithium, rubidium, and cesium using a Beckman Model DKII Ratio Recording Spectrophotometer. Chloride and sulfate in the anode solution were determined by standard gravimetric procedures.

A year was spent on calibrating the above outlined analytical procedures to insure accurate and reproducible results. Quartz samples were used to establish a suitable procedure for chemical analysis of inclusion materials. The last four calibrating runs are listed in Table 1. The two runs on sample

TABLE 1

CALIBRATION RUNS

IONS IN PARTS PER MILLION PER KILOGRAM OF SAMPLE

Sample	Na	K	Na/K	Li	Rb	Cs	Cl	SO_4
16	130	90	1.45	0.91	0.1	0.1	50	5
16	107	75	1.43	0.95	0.1	0.1	41	6
23	85	445	0.19	0.70	1.23	0.20	120	140
23	85	440	0.20	0.62	1.22	0.15	117	139

16–Quartz pod in simple pegmatite, Farmington, Canyon Complex, Utah.
23–Chert nodules in limestone, apparently primary.

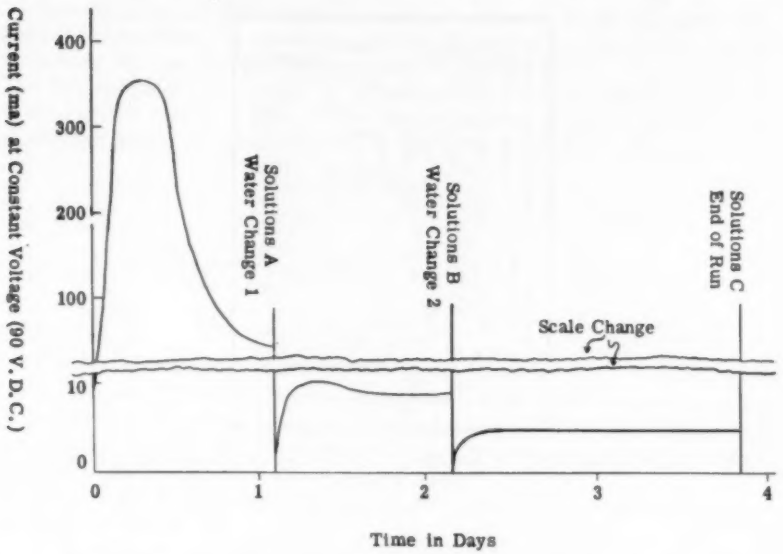

Figure 3. Typical Electrodialysis Cell Current Flow

16 were not electrodialyzed for the same length of time. Similar sodium to potassium ratios, however, indicate that the analytical techniques are valid despite the fact that inclusion ions are not quantitatively removed.

SAMPLING

Single crystals of galena, barite, and fluorite that obviously grew in open cavities were selected for study. Single crystals growing in open spaces cannot contain inclusions of fluids other than those that contributed to the primary crystal growth. Secondary inclusions are to be avoided because ball-milling will yield the sum of the secondary and primary inclusion materials.

Samples with primary fluid inclusions only were obtained from the Portales lead mine in the Hansonburg district near Bingham, New Mexico, and the Alamo mine about 3.5 miles northeast of Derry, New Mexico (Fig. 4). Mineralization at the Portales mine occurs in limestones of Pennsylvanian age. Barite, fluorite, and galena characteristically are found as excellent crystals coating the walls of fissures and small solution caves. No replacement of the limestone by the above minerals was noted, probably because of a silicification one to four inches in thickness of the limestone wallrock prior to mineral deposition.

At the Alamo mine, the geology and mode of mineral occurrence are practically the same as at the Portales mine, with the exception that fluorite alone is the ore mineral here.

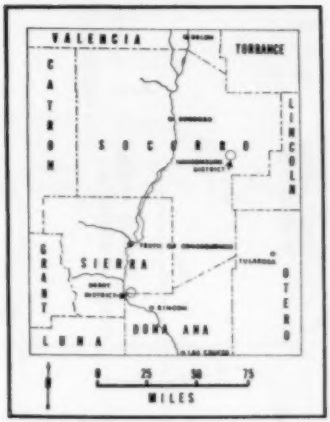

FIG. 4. Index map showing locations of the Derry and Hansonburg districts, New Mexico.

RESULTS

Results of the inclusion analyses are listed in Table 2. The amounts of calcium, magnesium, aluminum, and copper were obtained on the arc spectrograph by Professor Harold R. Bradford.

TABLE 2

Sample	Ions in parts per million per kilogram of sample											
	Na	K	Na/K	Li	Rb	Cs	Cl	SO_4	Ca	Al	Mg	Cu
Portales galena	8.8	3.8	2.3	0.1	tr	tr	116.1	—	tr	100.0	70.0	50.0
Portales barite	5.0	2.8	1.8	0.1	tr	tr	25.4	—	tr	150.0	60.0	100.0
Portales fluorite	1.3	15.0	0.1	tr	tr	tr	16.8	242.1	—	100.0	60.0	7.0
Alamo fluorite	6.3	50.0	0.1	0.1	tr	tr	16.8	560.0	—	80.0	50.0	6.0

Filling temperatures by the heated stage method were determined on the Portales fluorite, Portales barite, and Alamo fluorite. These temperatures of filling averaged 90° to 100° C, 130° to 140° C, and 105° to 115° C, respectively. Thus the samples, as listed in Table 2, are in their order of deposition. The physical evidence for depositional order also supports this sequence. Though these data on inclusion filling temperatures could hardly be called rigorous, they are sufficiently accurate to establish a depositional sequence.

Table 3 presents data on weight losses to 700° C. The Portales galena obviously could not be heated in an oxidizing atmosphere to obtain an accurate weight loss due to the loss of inclusion fluids alone. All samples decrepitated violently during heating. Covered fused silica crucibles stuffed with spun alumina were used to avoid weight losses from samples scattering.

Assuming that all the weight loss is due to included water, the concentrations of the resulting salt solutions would be 20 percent for the Portales barite, 26 percent for the Portales fluorite, and 37 percent for the Alamo fluorite. This last sample is rather high due to high sulfate, twice the amount as found in the Portales fluorite sample. This high value may be due to small crystals of included galena or some other sulfide, but none were observed.

TABLE 3

Sample	Per cent weight loss to 700° C
Portales fluorite	0.17
Portales barite	0.18
Alamo fluorite	0.19

CONCLUSIONS

The conclusions may be drawn as follows:

1. A trend of falling sodium to potassium ratio in correlation with falling temperature of inclusion filling is indicated in the Portales samples. This progressive potassic enrichment would be expected in the normal course of crystallization of a granitic source rock.

2. Chlorine is highest in the galena, indicating possible partial transport of lead as a chloride.

3. Despite the fact that the Portales fluorite appears to have more concentrated inclusion fluids than the earlier barite, the inclusion fluids become more dilute with decreasing temperature in the Portales mineral suite. Sulfate was not run on the Portales barite for obvious reasons, giving it an apparent lower fluid inclusion salt concentration than the Portales fluorite.

4. The general chemical composition of the inclusion fluids suggests continuity of the mineral depositing solution over the period of time represented by the Portales mineral suite.

5. Chemically, the Alamo and Portales fluorite samples are remarkably similar despite their being located approximately 90 miles apart. This similarity is due to a similar depositional environment and source for both deposits.

6. The low calcium values obtained on the Portales galena and Portales barite reflect the effective sealing of the limestone wallrock by the initial siliceous solutions. This "sealed" condition enhances the value of the inclusion data because it is unnecessary to attempt an evaluation of the effects of wallrock environment on the chemical composition of the inclusion fluids.

7. The deposition of fluorite in the Portales mineral suite does not necessarily indicate a sudden or sharp rise in the calcium content of the depositing solution. Recent work on the Poncha Springs, Colorado fluorite deposits (*7*), where fluorite is a minor constituent of the travertine being deposited at present, indicates a fluorine content of 12 ppm and 17 ppm calcium.

ACKNOWLEDGMENTS

The author wishes to acknowledge the helpful suggestions of Dr. Edwin W. Roedder during this study and L. B. Sand in preparing this manuscript.

The U. S. Geological Survey laboratories kindly made the temperature measurements. Financial assistance was furnished by the University of Utah Research Fund.

UNIVERSITY OF UTAH,
SALT LAKE CITY, UTAH,
May 4, 1957

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Economic Geology
Vol. 53, 1958, pp. 481–488

TUNGSTEN MINERALIZATION IN HONG KONG AND THE NEW TERRITORIES

S. G. DAVIS

ABSTRACT

Associated with the great batholith of acidic rocks on the East China coast tungsten ores occur in three main deposits: pegmatite, quartz veins and replacement.

Hong Kong has many typical ore occurrences that are found elsewhere in South China. There is much evidence, based on veins and dikes, that mineralization took place at much lower temperatures than have so far been postulated. In Hong Kong there is consistent evidence of tungsten-bearing quartz veins and stringers penetrating up to 300 feet into the country rocks and showing no signs of having produced the slightest metamorphism. Further consideration must be given to the behavior of melts and their eutectic mixtures. Hydrothermal alteration plays a very important part in the formation of epigenetic tungsten deposits.

The most common minerals in association with the tungsten ores are quartz, orthoclase, fluorite, beryl, molybdenite and muscovite. Some cassiterite and scheelite are also found close by.

The paragenesis of crystallization is not in all cases clear. However, when present the fluorspar crystallizes first and the quartz last. There is no well established order between these two extremes.

GENERAL GEOLOGY

THE area of Hong Kong and the New Territories forms one small part of the great batholith of acidic rocks that stretch from Hangchow Bay on the East China Coast southwest to Cambodia and Thailand. This batholith is not only complex in age but also in its composition. The oldest rocks appear to be associated with the mountain building of the Jurassic (Yen Shan No. 1). The later Laramide (Yen Shan No. 2) and Alpine revolutions also produced both extrusive and intrusive formations.

The rock however that everywhere dominates the topographic scene is a pinkish white granite. In Hong Kong this granite occurs in three main belts that trend in a SW–NE (Fig. 1). The most westerly belt comprises the barren rugged country that flanks both sides of Castle Peak Bay. The middle belt to the east starts in the Soko Islands and stretches northeasterly outcropping on many islands and reaching the mainland at Sham Shui Po and the area around Tide Cove. The third belt runs from Lamma Island in the south to Stanley Peninsula, Cape D'Aguilar and the Pu Toi Islands in the northeast.

The rocks intruded by the granite are predominantly older igneous rock: volcanics, porphyries and granodiorites, and some schist.

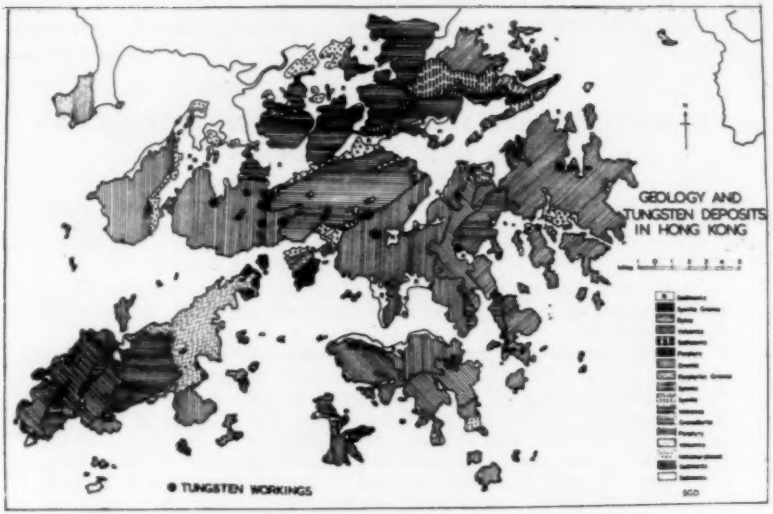

FIG. 1.

DISTRIBUTION OF DEPOSITS

The discovery of tungsten in South China dates back only to 1915. The armament requirements of World War I encouraged mining and very quickly China became the world's largest producer. The Colony of Hong Kong was also not slow in taking advantage of its deposits and began active exploitation in 1917.

The largest production of tungsten ore comes from underground mining but many stream beds and paddy fields have alluvial and placer deposits. Altogether there are 17 workings that can be classified as mines, only two are major workings (Needle Hill and Lin Fa Shan) using some mechanical equipment, and fifteen are minor workings. These minor workings are worked in primitive fashion employing the traditional Chinese style of shallow surface cuts and adits, which are limited in length and depth to the amount of fresh air available. Slow hand methods and poor dressing operations have resulted in low recovery.

Estimates of ore reserves have been hazarded from time to time but they vary so widely that they are not worth quoting. What is certain in Hong Kong is that the demand for wolfram is always satisfied and that the reserves are greater than were ever thought possible 40 years ago. In 1953, the most recent year of high production, approximately 50 tons of tungsten ore concentrate (mainly wolframite) were mined each month. The final ore concentrate usually contains about 65% WO_3.

MINERALIZATION

The main tungsten mineral of economic importance is wolframite. In one area however scheelite also occurs. The wolframite occurs in both pegmatite dikes and in fissure veins. Associated minerals are molybdenum, cassiterite, pyrite, quartz, orthoclase, fluorite, beryl, zircon, sphene, garnet, muscovite and biotite. In two areas the pegmatite granite has been altered to greisen. A characteristic of this greisen is the network of quartz veins representing infillings and replacements along the same fractures that gave access to the solutions causing the greisenization.

FIG. 2. Needle Hill Mine. Hand specimen. × 1¼.

Sequence of Mineralization.—The wolframite ores of Hong Kong occur in three main deposits: pegmatite, quartz vein, and replacement deposits.

A typical tungsten-bearing pegmatite is illustrated in Figure 2. The principal minerals present are wolframite, orthoclase and fluorite. At Devils Peak and Sheko (below Dragon's Back) large beryl crystals also occur in the pegmatite. The paragenesis is fluorite, which exhibits definite cubic form, followed by orthoclase felspar, which has been injected by the irregular shaped wolframite. The fluorite acted as the principal flux in the primary magma. As a consequence differentiation probably took place at lower temperatures than have normally been associated with wolframite.

A typical tungsten-bearing quartz vein deposit is illustrated in Figure 3. There are two main minerals only: wolframite and quartz. This represents the transition stage in which the pegmatites have graded into quartz veins and the felspars have completely disappeared. A regular feature of the quartz veins is that the further they are away from the main body of the intrusion

the narrower become the veinlets bearing the wolfram and the wolframite becomes coarser. Costly proof, typical everywhere in Hong Kong, that thick quartz veins and dikes (over 12 inches) are not likely to carry economic amounts of wolfram has been furnished in the Needle Hill Mine. Here two long adits follow what were first thought to be promising wide veins, but the cost of extraction was far too expensive in relation to the yields. The paragenesis is, first wolframite followed at a much later stage by the quartz. At Lin Fa Shan these quartz veins contain not only wolframite but cassiterite and small amounts of scheelite as well.

FIG. 3. Lin Fa Shan Mine. Hand specimen. × 1¼.

A typical fissure vein deposit is shown in Figure 4. It differs from the pegmatite because there is a much higher percentage of fluorite present with the wolframite and quartz. The paragenesis is clearly fluorspar first and then not so clearly wolframite and quartz possibly in this order. This type of fissure vein is farthest from the main body of the intrusion and is pyrometasomatic or contact-metamorphic. The invaded rock giving this specimen is a rhyolite from Sha Lo Wan, Lantau Island. In a similar geological occurrence at Ma On Shan besides wolframite there is garnet and fluorspar. The felspars have been largely altered to chlorite. The presence of garnet and fluorspar indicates conditions of high temperatures and pressures aided by suitable fluxes. At Ma On Shan a large lenticular mass of magnetite (proved reserve of 10 million tons) is located close to the wolfram-bearing rocks. This points also to hypothermal conditions. There is also evidence of grading from the quartz veins to the pyrometasomatic deposits. In the contact-metamorphic zones the effects on the invaded rocks vary widely. In some places the alteration consists chiefly of recrystallization due to heat and supersaturated solutions.

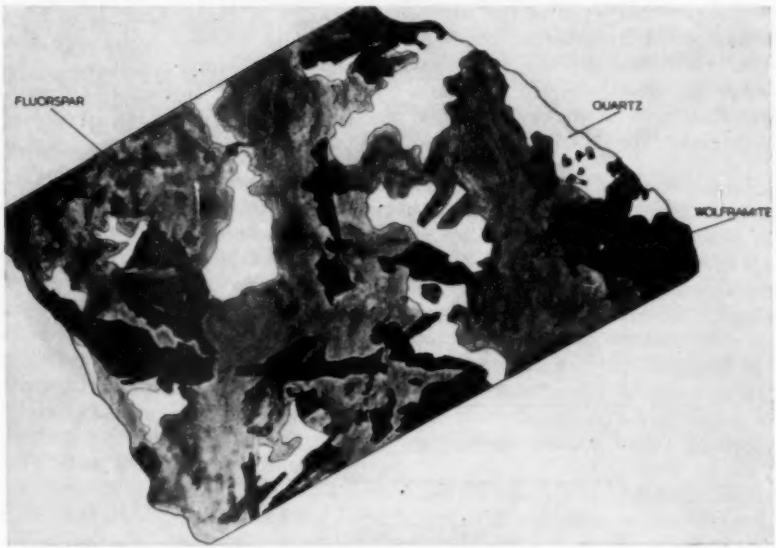

FIG. 4. Sha Lo Wan Mine. Hand specimen. × 1½.

An analysis of wolframite ore from Castle Peak (Fig. 5) is shown in Table 1.

TABLE 1

ANALYSIS OF WOLFRAMITE ORE, MARSMAN MINE, CASTLE PEAK, N. T.

WO3	65.27%
Sn	2.14%
Cu	Negative
As	0.02%
Sb	Negative
Bi	1.87%
Mo	Negative
P	Negative
S	0.12%
Mn	3.38%
Pb	Negative
Zn	Traces

In Hong Kong erosion of great thicknesses of the upper country rocks has revealed the present outcrops of pegmatites and contact-metamorphic deposits. If the widely supported theory that pyrometasomatic deposits form at from 400° C to 800° C, at high pressures, and at depths of from 1 to 2 miles it will be readily seen that mountain building in Hong Kong and South China was originally above 7,000 feet. Practically everywhere the zone of metallization is at 500 to 1,000 feet above sea level. At Castle Peak, northern Lantau, Wong Nai Tung, Ho Chung and Sokku Wan (Lamma Island) tungsten deposits occur at lower levels due to lateral contacts. Although there

is evidence that some of the wolframite deposits in Hong Kong have been formed under hypothermal conditions there is also evidence to indicate that other wolframite deposits were formed under mesothermal conditions. The depositing agents seem to have been largely liquid. A. Holmes (9) throws important light on this crystallization problem in discussing the rate of cooling of magma. He says, "Crystals can grow only if the atomic groups of which

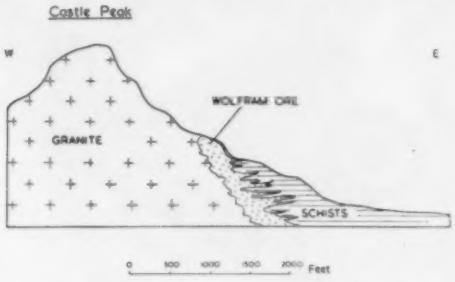

Fig. 5 Cross Section Contact Metamorphic Deposit At Castle Peak (Generalized)

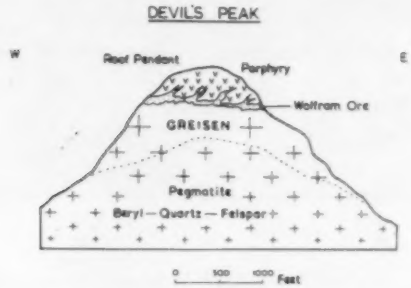

Fig. 6 Cross Section Contact Metamorphic Deposit At Devil's Peak (Generalized)

they are built have time to move towards the points where crystallization is beginning. In a viscous magma diffusion takes place more slowly than in a mobile magma, and consequently a second controlling factor is viscosity."

In Hong Kong there is consistent evidence of tungsten-bearing quartz veins and stringers penetrating up to 300 feet into the country rocks and showing no signs of having produced the slightest contact metamorphism. This phenomenon can only be explained by assuming that the temperature of the liquid magma was much lower than that required in experimental laboratory tests to produce crystallization of wolframite and quartz. It seems certain from the evidence of minerals found in the pyrosomatic zones at Lin Fa Shan, Devils Peak, and Sha Lo Wan that hydrothermal conditions together with carbon dioxide, hydrochloric acid, and fluoric acid were favorable aids in the crystallization of the melts.

A basic factor, which is possibly responsible for the dissolving of normally difficult fusible material is concerned with the original mixture. Teall (14) and Vogt (15) long ago suggested that intergrowths of orthoclase and quartz that form last in many igneous rocks and fissures are eutectic mixtures. Teall gave a mixture of 63.05 percent orthoclase 37.95 percent quartz as a mixture having maximum solubility. Vogt suggested 74.25 percent orthoclase and 25.75 percent quartz.

It is obvious that the crystallization of minerals takes place in complex solutions of many constituents. Minerals precipitate when the melt reaches a point at which the substance cannot be kept in solution chiefly because of lower temperatures. It is known that minerals do not necessarily form at the temperature of their melting point. The presence of other constituents act as catalysts and allow crystallization at much lower temperatures. Again there seems to be no well established sequence or order of crystallization or indeed mineralization. The work of N. L. Bowen on eutectic mixtures has demonstrated how involved and complex are the relationship of temperature, solubility, and mixtures. Field evidence in Hong Kong certainly points to the possibility that the temperatures at which mineralization took place were lower than laboratory evidence suggests.

The author in 1955, while on a United Nation Study tour of Senior Geologists in the U.S.S.R., visited the Department of Mineralogy, in the Institute of Geology, Academy of Sciences of Georgia, Tiflis. Here Professor G. V. Gvakhazia showed him a specimen that was predominantly stibnite enclosed in wolframite. Most antimony deposits are formed by hydrothermal solutions at low temperatures and shallow depth, giving rise to filled fissures, joints, and rock pores, and to irregular displacement deposits. The evidence of this specimen is of much interest because it indicates that later impregnated tungstate was at a sufficiently low temperature to crystallize without completely dissolving the stibnite, or even causing partial resorption of the mineral.

UNIVERSITY OF HONG KONG,
Nov. 18, 1957

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Economic Geology
Vol. 53, 1958, pp. 489–499

DISCUSSIONS

ON THE OCCURRENCE OF URANIUM IN ANCIENT CONGLOMERATES

Sir: Professor C. F. Davidson in his recent artcile on uranium in ancient conglomerates (3) has performed a most interesting work in collecting a wealth of information and arguments, which demonstrate some of the weak points in current theories on the sedimentary genesis of the Witwatersrand deposits. However, when he favors a hydrothermal hypothesis it should be realized that this is possible in part because our knowledge of the limitations of hydrothermal processes is so rudimentary in comparison to what is known about sedimentation. A mere reference to some similarities with the deposits of Shinkolobwe and Ruwe, which are clearly hydrothermal, is not enough, for important differences in geology, mineralogy, and geochemistry exist as well (for instance in the ratios U : Fe; U : S; U : Cu; Cu : Fe).

It may be said indeed, that to classify a mineral deposit as hydrothermal is often not much more than to state in scientific terms that we do not know very much of how it formed. Without well-based (not speculative) specifications on the nature, source and ducts of the hydrothermal fluids, and on the precipitating processes, the hydrothermal theory is by itself almost an *apriori deux ex machina,* which cannot be critically evaluated, proved or disproved. It thus belongs to the realms of personal preference. It is of no more concern to natural science than a flat statement that the uranium-bearing conglomerates were formed by some sedimentary process which in some unspecified way allowed for the difficulties pointed by Davidson. It is therefore felt that without denying the possibility of a hydrothermal origin for these deposits, and while awaiting the necessary qualifying statements from Davidson, one may well continue to look for exogene processes that might explain the ore deposition.

The main purpose of this discussion therefore is to point out that the geochemical evidence brought forward by Davidson seems to indicate in which directions to look.

The Thorium: Uranium Ratio.—Let us accept the world wide evidence that uraninite is not a persistent placer mineral, and that in highly weathered sediments, such as sandstones and conglomerates, the Th : U ratio is 10 or more, whereas in granite it is around 4. Both the instability of uraninite in placers and the relative enrichment of Th in weathered sediments are reasonably explained by the well known fact that uranium in the hexavalent state is easily transported in aqueous solutions. Th-compounds do not show a similar behavior. A sharp separation of U from Th might have been effected by this mechanism in the oxidizing waters that carried the clastic material and percolated through it before and after transport.

We also know that U is again precipitated under reducing conditions, even from very dilute solutions, e.g., this process is going on at the present time in the Baltic Sea (6). Thus the low Th:U ratio 1:30 in the conglomerate deposits may be explained simply by assuming that normal oxidizing conditions were followed by reducing ones during deposition.

The Sulfides.—The assumption that reducing conditions prevailed during the deposition of uraninite is not only a factor in support of a weak hypothesis. The typical association with sulfides by itself also indicates the same conclusion. (In passing it may be noted that reducing conditions may play a dominant role in the precipitation of uraninite from hydrothermal solutions. The common association with sulfides and even native silver gives clear evidence of this.) Although the sulfides are listed by Davidson in support of a hydrothermal hypothesis it must again be remarked that this assembly is also typically representative of the assemblage of elements found enriched in normal sediments of reducing environments, with which Davidson himself is particularly familiar (2), and with which (in other respects) he points out similarities (3, p. 679). The carbon content of the reefs may also point in the latter direction, for even if the polymerization hypothesis (4, 1) is accepted for the present form of Witwatersrand carbonaceous matter, its source is not known. That the carbon may be indigenous to the bankets is more probable than the belief that it is derived from overlying carbonaceous Karroo beds. Thucholite is also found in the Algom-Quirke deposit (8).

Brannerite.—Brannerite has remained a rare mineral in spite of the prolonged search for uranium minerals. S. W. Holmes (5) has collected the reports of its occurrences, and from this compilation it is evident that brannerite is found in pyrite-bearing conglomerates, in placers, in granitic and dioritic rocks, in pegmatite, and in quartz dikes of pegmatitic or metamorphic derivation. Brannerite thus has not been found as a member of a typical sulfide- or uranium-bearing hydrothermal paragenesis. The brannerite- and pyrite-bearing conglomerates may be explained as fossil brannerite placers, as has been proposed by Holmes. If so, one should normally expect corresponding contents of Th, Nb, Ta and rare earths. Of course this does not apply if the source was poor in these elements. Again in sulfidization of ordinary black sands-bearing conglomerates, considerable amounts of TiO_2 are set free, and this may stabilize uranium or form brannerite immediately, or later through metamorphism or heating prior to mineralogical examination.

Gold.—Contrary to Davidson's contention, it is evident from his table on p. 670 and especially from the case of Blind River, that there is no general positive correlation between uranium and gold, whereas there seems to exist such a correlation with pyrite, as shown by Holmes (5, p. 127) and for Au (5, p. 128). The correlation with gold, which does exist on the Rand, does not by itself prove that gold and uranium are of the same origin. For instance the occurrence of gold can be controlled by the concentration of heavy accessories in the coarse beds of a sedimentary series, whereas the uranium content can be dependent on the higher permeability in these same beds.

Summary of the Evidence.—To summarise then, the evidence from the Th:U ratio, the association with sulphides, and the correlation of uranium

and gold on the Rand, are inconclusive. The mineralogical evidence of the occurrence of brannerite is, if at all, in support of a sedimentary hypothesis. The eventual conclusions on the origin of the uranium in ancient conglomerates are not necessarily applicable to the problem of the gold of the Rand, and vice versa. However, results are not all negative. Positive conclusions are that uranium in these deposits is associated with sulfides (are the gold-bearing conglomerates of Tarkwa and Abossa, which contain hematite and ilmenite (no pyrite), not uraniferous?) (7, p. 246), and that both the low Th : U ratio and the presence of sulfides indicate reducing conditions during deposition. Through Davidson's work the problem of the origin of the Rand uranium deposits may be formulated like this: During what stage of the geological development of the Witwatersrand system can reducing conditions have prevailed, and which processes were the operative ones?

Davidson seems to discard sedimentary processes at the outset in spite of the fact that we know other sediments of reducing environments (black shales for instance) which show great geochemical similarities with the reefs by the combination of uranium, carbon, sulfides and ferrides. Reducing conditions and development of H_2S are found in parts of present-day deltas and other types of sedimentary environments.

To the writer, analogies with actualistic conditions in parts of western Africa seem especially suggestive. Here regional tilting and uplift have given rise to retreating escarpments, beneath which deserts spread to the coast. These deserts are transected by rivers, which in their upper reaches are quite normal. The water they carry and receive should be able to leach available uranium, whereas thorium would stay in its refractive minerals. In the lower parts of their courses these rivers, for instance Rio Giraul in the Mossamedes Desert, Angola, flow through coarse gravel beds buried in places under considerable covers of sand, thus effectively cut off from the oxygen supply of the atmosphere. (A great part of the oxygen in surface waters is a product of photosynthesis by plants and this evidently cannot go on in the absence of light.) Although very little is actually known, conditions should here become reducing through the effect of ferrous compounds in the permeated sediments and organic remains in the water. These superficially dry, submerged rivers reach to ocean, and beach-gravel placers are found near some of them. The ultimately preserved sediments consequently may combine desert-, marine- and fluviatile characteristics.

It is not for the writer to decide whether this or any other sedimentary environment is applicable to the Rand, or whether the uranium and sulfidization are hydrothermal, these questions must be returned to specialists on sedimentation and local geology. The writer is content if he has succeeded in demonstrating anew the complexity of the genetic problems and some of the possible implications of Davidson's evidence.

O. Brotzen

Mining Department,
University of Stockholm, Sweden,
Feb. 15, 1958

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Sir: Professor Davidson's paper "On the Occurrence of Uranium in Ancient Conglomerates" (Vol. 52, pp. 668–693) was both stimulating and interesting to one with a less extensive experience of these deposits. It happens, however, that I am acquainted with the little-known Jacobina deposit and also with the West African conglomerates which Professor Davidson does not mention, and I would like to make one or two points in connection with these.

So far as Jacobina is concerned, Professor Davidson states, "It has not yet been demonstrated that the rocks are adequately mineralised to warrant large scale mining for any of the contained minerals." The operative phrases are no doubt 'not yet' and 'large scale,' but there can be little doubt of the potential. My knowledge of this deposit is based on a professional visit, and it will be appreciated therefore that I am unable to quote figures, but I can say that systematic sampling of the outcrop of the pyritose reef, carried out by Dr. G. F. Flaherty, showed average gold values better than those quoted, and certainly economic. Values in depth approached three times those of the outcrop samples, and field evidence strongly suggested that the lower outcrop values are due to leaching with concomitant enrichment in depth, and it is doubtful if the primary zone has been reached at the depth quoted by White.

It thus becomes a little difficult to understand why White says, "further studies will be needed to determine the reasons for the absence of uranium in the weathered outcrop as opposed to its presence in the fresh pyritic ore-bodies at depth." The West African conglomerates, as Professor Davidson mentions in another publication, are essentially devoid of uranium. It is also a fact that they are non-pyritic, but that the cementing material of the pebbles contains a high proportion of hematite. Professor Davidson will no doubt agree that in this unique area the evidence for a hydrothermal origin of the

mineralization is less convincing. It would be extremely interesting to have his comment on this area.

G. A. SCHNELLMANN

MACKAY AND SCHNELLMAN,
115. MOORGATE, E.C.2.,
LONDON, ENGLAND,
February 5, 1958

ORE GENESIS—THE SOURCE BED CONCEPT

Sir: In the above article, C. L. Knight (1) postulates that "all sulfide orebodies of the majority of fields are derived from sulfides that were deposited syngenetically at one particular horizon of the sedimentary basin constituting the field, and that the sulfides subsequently migrated in varying degree under the influence of rise in temperature of the rock environment."

This seems to me to be a great over-simplification of a complex problem. In my opinion, certain types of metalliferous provinces commonly do have this origin. Thus, I have stated previously in this Journal (4), "most lead-zinc provinces are co-extensive with definite sedimentary rock groups." Most of Knight's examples are of this class. Uranium ores are also, in many cases, accumulated from sedimentary source rocks. In short, sedimentary rocks, during metamorphism and granitization, yield such metals as may be accumulated by sedimentational processes, and may be concentrated by metamorphism.

However, there is a large class of sulphide-forming metals for which basic igneous rocks, for example, not sediments, are the dominant source. Thus, the magnesium-rich igneous rocks contain a great deal more nickel than do most sediments, and important nickel sulphides are generally associated with such rocks. This is so, even where there is evidence of nickel-sulphide concentration by post-basic rock metamorphism. Many cobalt and copper deposits have a similar genetic association, and I suppose that few would ascribe the sulphide-native copper ores in basalts to a sedimentary origin.

Knight's concept that all of the great variety of ores in the Canadian Shield may be ascribed to a sedimentary control, is distinctly difficult to sustain. The patches of sedimentary and volcanic rocks, to which Gill refers, are remnants in a vast area of granitization and metamorphism. Just as the relatively thermally unstable sulphides accumulate at the edges of granitic bodies, so, similarly, the sulphide ores of the Shield are in the lower-grade metamorphic zones. Again, it is quite unrealistic to equate, genetically, the sulphides in the Mississagi conglomerate at Blind River, with the copper and nickel sulphides associated with the Sudbury norite, or with similar sulphides in the Moak Lake peridotite of Manitoba.

There are numerous and diverse source rocks for various metals; further, the concentration of numerous sulphide deposits, such as those associated with post-metamorphic basic dikes, cannot be ascribed to metamorphic processes at all.

Knight states (page 816), "the author proposes the source bed concept." In 1949 (2), I made a comparison between metalliferous geology and oil

geology from whence I drew the source bed analogy: "it will be seen, on the above tentative concepts, the search for ore becomes somewhat analogous to the search for oil. Metals disseminated in volcanic (meaning basic igneous rocks of all types) and sedimentary *source rocks* are expressed out during the process of granitization . . . ." The source rock idea was again discussed at length in papers published in 1954 (3) and early in 1957 (4). A classification of metalliferous provinces and deposits with respect to source rocks was given at the International Geological Congress at Mexico City in 1956 and was published in 1957 (5).

C. J. SULLIVAN

KENNCO EXPLORATIONS (CANADA) LTD.,
SUITE #1910, 25 KING STREET WEST,
TORONTO 1, CANADA,
January 30, 1958

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SOLUBILITY OF METAL SULFIDES IN DILUTE VEIN FORMING SOLUTIONS

Sir: Preparatory to starting experimental work on solubilities of metal sulfides in polysulfide solutions, an extensive review of the literature was made. As a result it was found that Garrels (1), in the paper of the title given above, had calculated copper solubilities in terms of a complex of divalent copper and divalent sulfur CuS_3^{-4}. His data for the solubilities were taken from Höltje and Beckert (2), however, who worked only with polysulfide solutions. A reexamination (3) of Garrels' work showed that the sulfur content of the polysulfide solutions had been recalculated in terms of H_2S, HS^-, and $S^=$ concentrations. Since this should have been done in terms of $S_2^=$, $S_3^=$, etc. as well as H_2S, HS^-, and $S^=$, the derivation of the formula, CuS_3^{-4}, for the complex is incorrect.

Höltje and Beckert's solubility determinations are reproduced in graphical form in Figures 1, 2, and 3. Figure 1 shows the marked increase of solubility of CuS with sulfur content at constant temperature and nearly constant ionic strength. Figure 2 shows the change of solubility with temperature at constant sulfur content and nearly constant ionic strength, and Figure 3 shows the change with ionic strength at constant temperature and average index of polysulfidation.

To define the average index of polysulfidation one may start with a solution of known concentration, c, of sodium sulfide, containing no excess sulfur. Solid sulfur is then dissolved in the solution. The average index of poly-

sulfidation, $\bar{y}$, is then the ratio of total sulfur (c plus solid S dissolved) to c; $\bar{y} = \frac{c + S_{diss}}{c}$. Thus if there are no polysulfides, $\bar{y} = 1$.

Because of the large number of ions possible it is very difficult to determine the concentration of each at any specified $\bar{y}$, ionic strength, and temperature.

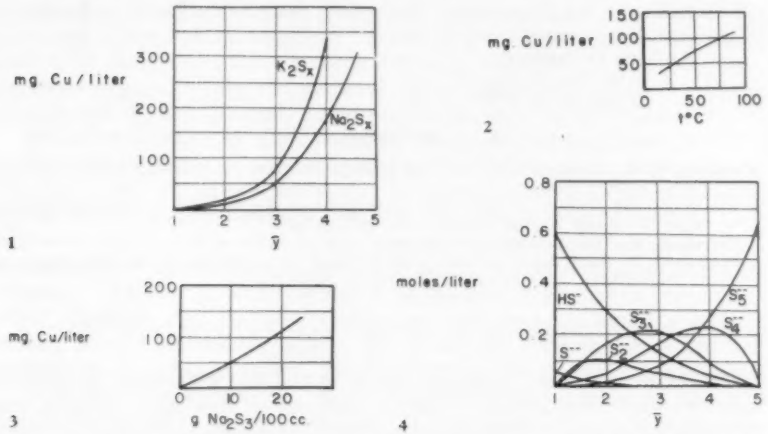

FIG. 1. Variation of dissolved copper with sulfur content ($\bar{y}$) in potassium and sodium polysulfides. 0.64 mole polysulfide/liter (5 g. Na_2S or 7 g. K_2S/100 cc.), 25° C. (Modified after Höltje and Beckert (2).)

FIG. 2. Variation of solubility with temperature. 10 g. Na_2S_3/100 cc. (After Höltje and Beckert (2).)

FIG. 3. Variation of solubility with concentration of Na_2S_3, 25° C. (After Höltje and Beckert (2).)

FIG. 4. Distribution of sulfide and polysulfide species as a function of total sulfur content, ($\bar{y}$), at 25° C., c = 0.64 moles/liter. (Calculated after Peschanski and Valensi (4).)

The best attempt known to the author has been made by Peschanski and Valensi (4). The author has used their data to calculate the distribution for c, as defined above, equal to 0.64 moles/l. The results are shown graphically in Figure 4.

Comparison of Figures 1 and 4 suggests that the pentasulfide ion S_5^{--} is principally responsible for the solubility of CuS in polysulfide solutions. Calculation of the ratio $K = \frac{(Cu^+)\ (S_5^{--})}{(\text{dissolved Cu})}$ gives a value of about 10^{-21} at 25° C. This value changes somewhat with both $\bar{y}$ and ionic strength; its temperature change could not be evaluated. (The concentration of cuprous ion was calculated from the Eh values given by Peschanski and Valensi, E° for the couple Cu^{++}/Cu^+, and the solubility products of Cu_2S and CuS by using well known chemical equations.) The similar ratio for cupric ion showed greater variation. It seems probable, therefore, that the complex in question is CuS_5^-.

It is hoped that a better understanding of the relations will result from experimental work now being started. This work is designed to determine solubilities of metal sulfides at various temperatures, ionic strengths, and indices of polysulfidation. The attempt will be made to measure sulfide ion activities by use of metal-metal sulfide electrodes, such as Ag/Ag_2S, as well as pH and Eh.

PAUL L. CLOKE

DUNBAR LABORATORY,
HARVARD UNIVERSITY,
CAMBRIDGE, MASS.,
January 29, 1958

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2. Höltje, R., and Beckert, J., 1935, Die Löslichkeit von Kupfersulfid in Alkalipolysulfidlösungen: Z. anorg. Allgem. Chem., v. 222, p. 240–244.
3. Garrels, R. M., 1957, personal communication.
4. Peschanski, D., and Valensi, G., 1949, Contribution à l'Electrochimie des Solutions Aqueuses de Polysulfures: Jour. Chim. Phys., v. 46, p. 602–619.

PROFESSIONAL ETHICS OF GEOLOGISTS

Sir: The interesting articles in Vols. 51 and 52[1] pertaining to desirable rules of conduct and unethical practices indicate, as does other evidence, that there is a widespread concern among economic geologists and teachers of geology with these problems. This concern is shared by others who are not geologists, including investors and those importuned to become investors in enterprises or proposed enterprises concerned with mineral deposits. Ethical standards that affect the relationships of geologists to one another or to their employers are of special consequence to geologists and to individuals and organizations that employ them, but ethical standards that affect the general public have a much wider and much more serious and important impact. Those geologists who, like the writer, have read many geological and engineering reports used to promote the public sale of securities of mining ventures are keenly aware of the ethical deficiencies revealed by some of the reports and of the great benefit that would be derived from improving the ethical standards of the writers.

What are the reasons for the deficiencies in the ethical standards of some geologists?

Of course there is no pat answer to such a question. Some of the explanations lie in the province of the philosopher or psychologist; defects in character are the roots of the noxious weed of dishonesty. If, as appears to be the case, there has been an increase in recent years in the number of geologists

[1] "To Teachers of Geology"—Charles F. Park Jr., vol. 51, no. 6. "The Mining Exploration Man, His Ethics—A Professional Challenge"—Thomas W. Mitchum, vol. 51, no. 6. "Ethics and Conduct"—Thomas W. Mitchum, vol. 52, no. 2. "To Teachers of Geology; The Mining Exploration Man, His Ethics—A Professional Challenge"—Charles H. Behre Jr., vol. 52, no. 2. "Professional Ethics and Conduct for Economic Geologists"—D. M. Davidson, vol. 52, no. 3. "Professional Ethics"—V. L. Bosazza, vol. 52, no. 4. "Professional Ethics and conduct for Economic Geologists"—John Eliot Allen, vol. 52, no. 7.

guilty of unethical professional practices and conduct, part of the reasons stem from technological developments and economic conditions that have expanded the opportunities of economic geologists to make money and have increased the temptation to do so at the expense of ethical standards. Perhaps the insufficiency of effective ethical indoctrination of students in schools and universities by teachers dedicated to the task is responsible for part of the deficiencies in ethical standards of some geologists. Another reason may be that the prevailing individualistic character of the profession may place too much burden on the independent geologist forced to establish and depend upon his own ethical standards, and he needs the guidance and support of precepts promulgated by, and generally agreed to, by members of his profession.

What can be done to improve ethical standards and practices?

Again there seems no pat answer. Legal measures have a limited scope. The corrective force of retribution may be salutary in some cases. Collective actions that geologists themselves can take might have much influence. One of these actions could be more written and oral discussions to increase awareness of the problems among geologists and others, and to elicit ideas and exert influence. Another is concerted action by teachers of geology in the universities. Another may be the promulgation and dissemination of a suitable written code of professional ethics. By a "suitable code" is meant one that is inspirational, ethically sound, practical and universally applicable.

It appears that such a code would be helpful to geologists of all ages and would also be useful to some who are not geologists. Teachers of geology, who have exceptional opportunities to exert a beneficial influence on the ethics of future geologists, can, as Charles Park has written, follow their "own carefully thought out code of conduct." But perhaps, as John Allen has indicated, it would be helpful to teachers to have a "Bible," so to speak, for their use, and to which students could be referred. I venture to suggest that practically all economic geologists, some time in their careers, have problems in ethical standards affecting themselves and others which a suitable written code of ethics would help to resolve. There is evidence that some geologists act unethically at times without adequate realization of the ethics involved. It seems likely that such men would be benefited by a suitable written code.

Is it feasible to devise a suitable written code for economic geologists and if so what group should do so? It seems to me that it is difficult to know without making the trial but, if it is feasible, the Society of Economic Geologists seems to be an appropriate group to do so.

The Report of the Committee on Ethics and Conduct in vol. 50, no. 5 of ECONOMIC GEOLOGY presents reasons for recommending that "no attempt be made at this time to draw up a written code of ethics." Among the reasons is the belief of the Committee "that good vs bad ethics are relative matters that are influenced by many and varying factors, including the custom of one's fellows, custom within the particular country and the segment of society of which one forms a part, the particular regulations that govern one's relationships to associates, the purpose and rules governing one's employment, etc, etc." And "The details of good ethics cannot be defined, therefore, other than within the framework of particular or known circumstances." More-

over, "past and present standards" (of the Society of Economic Geologists) "were not established by imposing written rules of conduct in the form of codes," but rather by other factors that are mentioned in the report.

On the other hand some of the articles in ECONOMIC GEOLOGY indicate that some geologists may favor having a written code of ethics. Thomas Mitchum proposes statements, similar to those he sets forth, for inclusion in such a code and John Allen makes a specific recommendation for deriving a code scientifically.

The conclusions of the Committee seem sound with respect to a formal written code of ethics that attempts to promulgate rigid and restrictive rules of conduct for members of the Society of Economic Geologists. It appears that such a code is unnecessary and might be objectionable. But a code that skillfully steers a course between rigid, controversial or otherwise objectionable pronouncements on the one hand, and abstract generalities on the other, would be quite a different matter. Perhaps a suitable code should concern itself fundamentally with pertinent ethical principles. Certainly it should not attempt to say yes or no categorically to questions that should only be answered yes or no according to circumstances. Questions involving dishonest practices are amenable to unqualified definitions and condemnation, and intellectual dishonesty, which is an ingredient of many unethical practices, should be susceptible to satisfactory treatment. So should such subjects as conscientious service, violation of confidential information, and plagarism. But such questions as length of service to employers, use of knowledge gained during employment, fees, competition with colleagues, advertising of services, accepting payment for services in shares, contingent interests, options on shares, "playing" the stock market, and others, may be either black or white depending upon circumstances. Spelling out of the circumstances under which various actions or practices are or are not ethical would be an especially desirable feature of a code. Perhaps by avoiding an inflexible position, but setting forth enlightening principles, such matters can be dealt with satisfactorily in a written code.

The Society of Economic Geologists seems to be an appropriate organization to formulate a code for economic geologists concerned with the fields of endeavor in which members of the Society are active. The use and value of a code would be restricted unless it were applicable, well-known, and influential among economic geologists in general. Most of the economic geologists needing guidance and surveillance are not members of the Society. Perhaps there is a special need for improvement in the ethical standards of some members of the Society pertaining to relationships among geologists and to relationships of geologists to employers but, so far as my experience in North America shows, unethical conduct that directly injures the public is chiefly, if not entirely, the fault of non-members of the Society.

It is difficult to be sure without trial whether it is feasible to devise a suitable written code of ethics. But is it not worth while to determine if it is? I propose that the views of the members be ascertained on whether an attempt should be made to prepare a suitable code, and if the response is affirmative

that a committee be appointed to prepare a draft of a code, that the draft be submitted to members for comment and suggestions (more than once if called for), that revisions be made where advisable, and finally that the proposed code in finished form be submitted for approval or rejection by members of the Society. Even if it proves to be infeasible to promulgate a suitable code the ideas elicited in attempting to do so may be rewarding.

ELLSWORTH Y. DOUGHERTY

1328 MIDDLETON COURT,
LOS ALTOS, CALIF.,
January 20, 1958

Economic Geology
Vol. 53, 1958, pp. 500–508

REVIEWS

Mineraly urana: spravochnik. (Minerals of Uranium: A Reference Book.) By M. V. SOBOLEVA and I. A. LUDOVKINA. Pp. 408, figs. 206, three folding tables. Gosgeoltekhizdat, Moscow, 1957. Price (bound) 20 r. 90 k. (about $2.50). Russian only.

This comprehensive text on the mineralogy of uranium went to press early in 1956 and incorporates in a sometimes uncritical compilation most of the relevant literature prior to that date. Of the 439 works mentioned in a list of references, 104 are in Russian and 335 in western languages. About 150 uranium minerals (excluding synonyms) are described, in each case with details of physical properties and crystallography and with often numerous chemical analyses, followed in many instances by x-ray diffraction data, optical constants, and information on parageneses. No mention is made of localities of derivation. The work gives the fullest account yet published (50 pages) on the oxide minerals of uranium, distinguishing by chemical composition or physical properties four varieties of uraninite (ulrichite), bröggerite, clevite, four varieties of nasturan or pitchblende, hydronasturan, uranium black, uranothorianite and aldanite. For western readers a special interest centers in descriptions of eleven new uranium minerals from the U.S.S.R., of which only orlite [$3PbO \cdot 3UO_3 \cdot 4SiO_2 \cdot 6H_2O$], lermontovite [$(U,Ca,TR)_3 \cdot (PO_4)_2 \cdot 6H_2O$], iriginite [$UO_3 \cdot 2MoO_3 \cdot 4H_2O$], przhevalskite [$PbO \cdot 2UO_3 \cdot P_2O_5 \cdot 4H_2O$] and lodochnikite [$2(U,Th)O_2 \cdot 3UO_3 \cdot 14TiO_2$] are as yet well founded with x-ray data and chemical analyses. Ufertite, a uraniferous iron titanate, is virtually identical with davidite. Valid species which are not listed include abernathyite, kahlerite and cheralite; and omissions also include obruchevite, a urano-yttrian pyrochlore from Karelia. A tabulation of uranium minerals according to optical constants is given in an appendix. Unfortunately the printing of the illustrations does not attain the standard seen in some recent geological works from Russia; and both misprints and erroneous references are abundant, particularly so in that part of the bibliography in the western languages. But notwithstanding these failings, this is an outstanding contribution to the fundamental literature of radiogeology. A great many of the chemical analyses and other data listed are new, and consequently the text does much to make up for the complete lack of Russian publications on uranium mineralogy within the decade 1945–55.

C. F. DAVIDSON

UNIVERSITY OF ST. ANDREWS,
SCOTLAND,
Apr. 8, 1958

The Powder Method in X-Ray Crystallography. By LEONID V. AZÁROFF and MARTIN J. BUERGER. Pp. 342. McGraw-Hill Book Co., New York, 1958. Price, $8.75.

The authors state that the purpose of this book is to supply training for students in making and interpreting powder photographs. The book contains a complete exposition of the principles and utilization of the powder method. There are 16

chapters and 5 appendices. These deal with the theory and principles, design, procedures, relation of spacings to cell geometry, interpretations, indexing, errors, accuracy, reciprocal lattice, reduced cells, homogeneous axes and Delaunay reduction, identification and appearance of powder photographs. The lengthy appendices cover quadratic forms, conversion of d to Q, and extrapolation functions.

The book grew out of notes for lectures to students in preparing them to use, interpret, and index powder photographs. The discussion is kept on a fundamental plane and the mathematics used is simple. The principles are illustrated by detailed examples.

This book should prove to be the standard text on the powder x-ray method.

Geography in the 20th Century. 3rd Edit. Edited by GRIFFITH TAYLOR. Pp. 674; figs. 57; pl. 15. Philosophical Library, New York, 1958. Price, $.75.

This book was first published in New York and London in 1951. A second edition revised and enlarged appeared in 1953. In this third edition one new chapter on The Relations of Geography and History by H. C. Darby has been added and Chapter 13 on Exploration in the Antarctic by Griffith Taylor has been enlarged and brought up to date. Otherwise this volume is the same as the second edition, which was previously reviewed in these columns. It is composed of the writings of 22 authors, most of which were contributed for this volume; a few are reprintings of articles of deceased authors.

The book is divided into 3 parts. Part I, The Evolution of Geography and its Philosophical Basis, consists of 7 chapters dealing chiefly with different national viewpoints of geography. Part II, The Environment as a Factor, has 10 chapters mostly dealing with regional geography. The third part has 13 chapters on Special Fields of Geography, and covers field work, sociological and urban aspects, the function of geographical society, and "geo-pacifics," by the editor.

The predecessor volume has proved a useful one, and so will this edition.

Progress of the Mineral Industry of India 1906–1955. Pp. 567. Mining, Geological and Metallurgical Institute of India, Calcutta, 1957.

The Institute has extended itself in publishing this large volume in celebration of its 50th Anniversary. There are 64 contributors who cover all phases of the Indian mineral industry. The subjects covered are history and progress in geology, fuel industries (atomic, coal, oil), paleontology and paleobotany, metalliferous and non-metalliferous industries, scientific departments, learned societies and mining associations. It concludes with a classified list and author index of the transactions of the Institute.

The parts in geology include: Structural and Stratigraphic Geology by D. N. Wadia; Earthquakes by W. D. West; Petrology by A. G. Thingran; Economic Geology by J. A. Dunn and A. K. Dey; Engineering Geology by K. K. Dutta, M. S. Balasundaram, and P. C. Hayra; Ground-Water by P. K. Ghosh and G. C. Chaterji; Paleontology and Paleobotany by M. R. Sanhi.

Under the mineral industries, coal and iron and steel receive extensive treatments. It is estimated that some 2 million tons of monazite are available containing 150,000 to 180,000 tons of thorium. Uranium is estimated to be 6 to 7 thousand tons. There are some 41,000 million tons of non-coking coal and lignite. In iron ore reserves India is among the four top nations and probably is the first with some 21,300 million tons of ore containing 12,000 million tons of iron. Manganese reserves are estimated to be 175 million tons.

The volume brings together full information regarding the mineral industry of India, including geology, mining, and metallurgy. It should serve a very useful purpose to all interested in India.

Canadian Resources, Part I, Alberta, British Columbia, Manitoba, Saskatchewan. Stanford Research Institute, Menlo Park, Calif., 1958. Price, $10.00.

This loose-leaf volume of data sheets is the first of others to appear on Canada. Under each of the provinces there is given a reference map, climate, production, consumer price indices, population, employment, income, agriculture, fur, minerals, forests, energy (including coal, oil, gas, and reserves), manufacturing, construction, and transportation. The data sheets cover periods of years. For example, the production and value of coal, gas, and oil are given from 1920 to 1956. Similar data are given for 11 minerals in British Columbia. The data sheets are so arranged that each of the provinces can be compared with the other.

The book brings together a mass of statistical data available for ready reference.

Block Diagrams, and Other Graphic Methods Used in Geology and Geography. 2nd Edit. By A. K. LOBECK. Pp. 212; figs. 288. Emerson-Trussell Book Co., Amherst, Mass., 1958. Price, $6.00.

Everyone is familiar with the first edition of this book, which appeared 33 years ago. The author's artistic and skillful sketches have been a guide to students during that entire interval.

This edition is really a reprinting, but about a dozen pages have been added at the ends of chapters where blank pages appeared before, and at the end of the book. These pages add new illustrations and new ideas relating to landscapes and field sketching, particularly sketches made from aerial photos such as were used for military purposes during the last war. Anyone will receive much pleasure from simply leafing it over and looking at the unexcelled sketches and diagrams. The text, however, is also a treatise on land forms.

Principles of Geochemistry. 2nd Edit. By BRIAN MASON. Pp. 310; figs. 48. John Wiley and Sons, New York, 1958.

Since the first edition of this book appeared in 1952 and was reviewed in this JOURNAL, the science of geochemistry has advanced by leaps and bounds. The author in his preface states "Particularly noteworthy have been the advances and techniques for age determination of rocks, the keen interest in the nature and composition of the earth's interior, the large amount of work on minor and trace elements . . . and the development of isotope geochemistry."

The author has introduced these materials into this new edition. He has superseded many of the data in the first edition by more reliable figures. The general organization of the first edition has been retained but there are numerous changes in details. The number of tables has been increased; several new figures added; and the pages have been increased from 276 to 310. The bibliographies accompanying each chapter have been thoroughly revised to include new sources of information.

With such a rapidly growing science the revisions in this new edition will be welcomed, and the book will continue to be a useful text and reference book.

BOOKS RECEIVED

JAMES M. ALLEN AND JOHN W. SALISBURY

Progress in Peaceful Uses of Atomic Energy July–December 1957. UNITED STATES ATOMIC ENERGY COMMISSION. Pp. 463; pls. 10; tbls. 11. Price, $1.25. U. S. Government Printing Office, Washington, D. C., 1957. *Includes an informative section on progress with radioisotopes used in basic research in physics and chemistry.*

Deformation of the Earth's Crust. WALTER H. BUCHER. Pp. 518; figs. 100. Hafner Publishing Co., New York, 1957. Price, $10.00. *A reprinting of the well known 1933 edition, with a new preface.*

Our Nuclear Adventure (Its Possibilities and Perils). D. G. ARNOTT. Pp. 170. Philosophical Library, New York, 1958. Price, $4.75. *A lucid assessment of potentialities and hazards of nuclear energy with emphasis on its constructive aspects.*

Minerals Yearbook 1954. Volume I. Metals and Minerals (Except Fuels). STAFF OF THE BUREAU OF MINES. Pp. 1,419. Price, $4.50. U. S. Government Printing Office, Washington, D. C., 1958. *Metals and nonmetals, including sections on these mineral industries, metallurgical technology, mining technology, statistical summary of mineral production, and employment and injuries.*

Minerals Yearbook 1954. Volume III. Area Reports. STAFF OF THE BUREAU OF MINES. Pp. 1,179. Price, $4.00. U. S. Government Printing Office, Washington, D. C., 1957. *Reports on the mineral industries of each state, territory, and possession of the United States.*

Diamond Resources of British Guiana. E. R. POLLARD, C. G. DIXON, and R. A. DUJARDIN. Pp. 43; figs. 10. Price, $1.00. (B. W. I.) British Guiana Geological Survey, Georgetown, 1957. *History of development, distribution, mode of occurrence, character of diamonds, extraction and production statistics. Diamonds occur as alluvial concentrations on slopes of sandstone plateau. Production declining.*

The Geology and Mineral Resources of the Kota Belud and Kudat Area North Borneo. E. A. STEPHENS. Pp. 137; pls. 47; figs. 18; tbls. 15. Price, 14s. Geological Survey British Territories in Borneo, Memoir 5, Kuching, Sarawak, 1956. *Examination of manganese, copper, chromite, and asbestos occurrence and oil seepages showed small chance of economic development. Two geologic maps, scales 1 : 50,000 and 1 : 125,000, in pocket.*

Bibliography of Graduate Theses on Geophysics in U. S. and Canadian Institutions. GEORGE E. TARBOX. Pp. 37. Price, $1.00. Quarterly of the Colorado School of Mines, Vol. 53, No. 1, Golden, 1958.

The Egyptian Journal of Geology, Vol. 1, No. 1. Pp. 84; pls. 7; figs. 19. Price, 50 P.T. The Geological Society of Egypt, Cario, 1957. *Four papers on: classification of Egyptian mineral deposits; igneous petrology; the Lias in Egypt; and Cenomanion foraminifera. In English.*

Review of Egyption Geology, Vol. I. Pp. 43. The Science Council, Cario, 1957. *Contains two sections. The first deals with historical geology, tectonics, geomorphology and Pleistocene geology, and the second with economic and engineering geology, ground water, mineralogy, Precambrian geology, and soils. In English.*

Bulletin de la Direction des Mines et de la Géologie, No. 8. Pp. 151; figs. 26; tbls. 7. Gouvernement Général de l'Afrique Équatoriale Française, Paris, 1958.

Description of work done in 1956. Data on ore deposits, regional mapping, drilling, geophysics and geochemistry. In French.

Boletin del Centro de Documentacion Cientifica y Tecnica de Mexico, Vol. 6, No. 8. Pp. 36. Secretairia de Educacion Publica, Mexico, 1957. *Annotated bibliography of recent papers in mathematics, astronomy, astrophysics, geology, geophysics, and geodesy. In Spanish.*

Production Statistics and Engineering Data, Oil in North Dakota, Second Half 1957. W. M. LAIRD. Pp. 50. Price, $1.00. North Dakota Geological Survey, Grand Forks, 1958.

Sixty-Fifth Annual Rept.. Vol. LXV, Pt. 7, 1956. Geology of the Clarendon-Dalhousie Area. B. L. SMITH. **The Geology of Darling Township and Part of Lavant Township.** P. A. PEACH. Pp. 60; pls. 22; fig. 1. Ontario Department of Mines, Toronto, 1958. *General geology, structure, and economic geology of two areas in the Grenville province in southeastern Ontario. Map, scale 1 inch: 1 mile.*

The Mineral Wealth of Madhya Pradesh, Vol. 1, No. 2. Pp. 28; figs. 4; tbls. 8. Department of Geology and Mining, Raipur, India, 1958. *Description of bauxite deposits, diamond preparation, mineral output for the year 1957.*

Report of the Geological Department 1956. Pp. 12; tbls. 2. Geological Survey of Sierra Leone, Freetown, 1957. Price, 1 sh. 6 d.

The Geology of the Eastern Soutpansberg and the Lowveld to the North. O. R. VAN EEDEN, H. N. VISSER, J. S. VAN ZYL, and others. Pp. 126; pls. 16; figs. 3; tbls. 17. Price 11 s. 6 d. Union of South Africa Department of Mines, Cape Town, 1955. *Explanation of the geologic map sheet 42 (Soutpansberg) included under separate cover. Map, scale 1:125,000.*

Earth for the Layman. M. W. PANGBORN, JR. Pp. 68. Price, $1.00. American Geological Institute Rept. 2, Washington, 1957. *A list of nearly 1,400 good books and pamphlets of popular interest on geology, mining, oil, maps, and related subjects.*

Directory of Independent Commercial Laboratories Performing Research and Development 1957. Pp. 57. National Science Foundation, Washington, 1958.

Service de la Carte Géologique de L'Algérie—Alger, 1955–1957.

Bull. 4. Contributions a l'Étude Géologique des Monts du Hodna. Le Massif du Bou Taleb. J. BERTRANEU. **La Région de Tocqueville et de Bordj-R'dir.** H. CRUYS. Pp. 326; pls. 13; figs. 36. *In French.*

Bull. 8. Travaux des Collaborateurs 1955. Pp. 392; pls. 34; tbls. 8. *Eighteen articles on various phases of geology. Seventeen geologic maps, cross-sections, and correlation charts under separate cover. In French. (Bull. No. 8—Atlas).*

Bull. 12. Étude Géologique des Bassins Néogènes Sublittoraux de L'Algérie Occidentale. ALAIN PERRODON. Pp. 328; pls. 12; figs. 96. *In French.*

Bureau of Mineral Resources, Geology and Geophysics—Australia, 1956–1957.

Rept. 29. The Geology of the South-Western Canning Basin, Western Australia. D. M. TRAVES, J. N. CASEY, and A. T. WELLS. Pp. 74; pl. 1; figs. 22; tbls. 4. *Prospects of finding commercial supplies of oil in the area are very remote. Geologic map, scale 1 inch: 10 miles.*

Summary Rept. 41. Mineral Resources of Australia—Natural Abrasives. Z. KALIX and J. BARRIE. Pp. 48; figs. 2; tbls. 20. Price, 3 sh. *Production, consumption, uses, overseas trade, buyers, and prices.*

Bull. 40. Permian Productacea of Western Australia. P. J. COLEMAN. Pp. 148; pls. 21; figs. 6; tbls. 3. *Distribution of the species in general confirms existing correlations within the province. The fauna as a whole has its closest affinities with the Permian productid fauna of Timor, and is essentially dissimilar to that of Eastern Australia.*

Geological Survey of Canada—Ottawa, 1957–1958.

National Advisory Committee on Research in the Geological Sciences. Seventh Annual Report 1956–57. Pp. 164. Price, 50 cents. *Report of research in various geological fields, with brief descriptions.*

Publications of the Dominion Observatory Ottawa. Vol. XIV. Bibliography of Seismology No. 20. W. E. T. SMITH. *Bibliography of seismographic publications for the period July–December 1956.*

Geological Survey of India—Calcutta, 1953–1956.

Series A, No. 5. Asbestos and Barytes in Pulivendla Taluk, Cuddapah District. M. S. KRISHNAN and M. S. VENKATRAM. Pp. 53; figs. 7. Price, 1 sh. 9 d. *Chrysotile asbestos occurs at contact of serpentinized dolomitic limestone and a traprock sill. Reserves estimated at 256,000 tons. Barite occurs in veins in the traprock and limestone. Reliable estimate of reserves not possible.*

Series A, No. 6. Magnesite. N. K. N. AIYENGAR. Pp. 46; pls. 9; figs. 3; tbls. 4. Price, 3 sh. 6 d. *Summary of nature, distribution, and uses of magnesite. Evaluations made of 20 major deposits. Reserves estimated where possible.*

Series A, No. 7. Chromite. M. S. KRISHNAN. Pp. 46; pl. 1; figs. 4; tbls. 5. Price, 2 sh. *Mineralogy, geology, uses, grades, treatment, and manufacturing uses of chromite. Indian deposits described as well as producers in other parts of the world.*

Series, A, No. 8. The Iron Ore Deposits of Parts of Salem and Trichinopoly Districts. M. S. KRISHNAN and N. K. N. AIYENGAR. Pp. 63; pls. 3; figs. 5; tbls. 4. Price, 3 sh. *Description of ferruginous quartzitic iron ores. Average grade about 35%; reserves 304,650,000 tons.*

Series A, No. 9. Iron-ore, Iron and Steel. M. S. KRISHNAN. Pp. 236; pls. 6; figs. 14; tbls. 31. Price, 9 sh. 3 d. *Description of deposits, utilization, and production statistics.*

Series A, No. 10. Economic Geology and Mineral Resources of Madhya Bharat. M. K. Roy Chowdhury. Pp. 83; pls. 5; tbls. 48. Price, 7 sh. 3 d. *Occurrence of economic minerals in central India.*

Series A, No. 11. The Nellore Mica Belt. B. C. ROY. Pp. 156; pl. 1; tbls. 20. Price, 5 sh. *The geology, mining, and marketing of mica, plus detailed descriptions of individual mines. The mica deposits of Nellore have been exploited for the last 50 year without showing signs of exhaustion, but modern mining methods must be applied or a good proportion of the recoverable mica will be lost.*

Mysore Geologists' Association—Bangalore, 1957.

Bull. 14. Bibliography of Mysore Geology 1955. B. P. RADHAKRISHNA. Pp. 16. *Bibliography and short summaries. In English.*

Bull. 15. Pillow Lavas from Mysore State, India. C. S. PICHAMUTHU. Pp. 23; pls. 12; fig. 1; tbl. 1. *Distribution, mode of occurrence, physical character, mineralogic and chemical composition of basic volcanics in Mysore.*

Geological Survey of Japan—Hisamoto-chō, Kawasaki-shi, 1957–1958.

Rept. 174. Geochemical Survey for Natural Gas Near Yaizu City, Shizuoka Prefecture. K. MOTOJIMA, S. MAKI and T. MITSUNASHI. Pp. 41; figs. 32; tbls. 2. *In Japanese.*

Explanatory Text of the Geological Map of Japan. Horozuki (Aomori-6). M. SAITO and F. UEMURA. Pp. 33; figs. 8. *Map area located in northeast Tsugaru Peninsula. Small lead-zinc ore bodies replace andesitic tuffs or rhyolite. Geologic map, scale 1:50,000. English abstract.*

Explanatory Text of the Geological Map of Japan. Kirishimayama (Kagoshima-74). K. SAWAMURA and K. MATSUI. Pp. 65; figs. 20; tbls. 4. *Map covers the area of the Kirishima volcano. Iron sulfide is recovered from the bottoms of lakes fed by hot springs, and sulfur is collected from fumarolic gases. Geologic map, scale 1:50,000. English abstract.*

Explanatory Text of the Geological Map of Japan. Kuraoka (Kagoshima-42). N. KAMBE. Pp. 62; figs. 25; tbls. 2. *Map area located in central Kyushu. Numerous small manganese and two large copper ore bodies described. Geologic map, scale 1:50,000. English abstract.*

Explanatory Text of the Geological Map of Japan. Yoshinoyama (Kyōto-75). K. HIRAYAMA and F. KISHIMOTO. Pp. 52; tbls. 3. *The Yoshinoyama sheet covers an area in the northern central part of the Kii Peninsula, containing small copper and mercury deposits. Geologic map, scale 1:50,000. English abstract.*

Explanatory Text of the Geological Map of Japan. Tangoyura (Kanazawa-76). O. HIROKAWA and K. KURODA. Pp. 32; figs. 3; tbls. 3. *Map area located on the west coast of Wakasa Bay, and contains a few small copper deposits. Geologic map, scale 1 :50,000. English abstract.*

Kansas Geological Survey—Lawrence, 1957.

Map. Oil and Gas Investigations No. 15. Preliminary Regional Structural Contour Map on Top of the Dakota Formation (Cretaceous) in Kansas. D. F. MERRIAM.

Bull. 127, Pt. 3. The Precambrian Rocks of Kansas. O. C. FARQUHAR. Pp. 49–122; pls. 9; figs. 4. *Configuration and geology of Precambrian surface determined from well records.*

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Bull. 127, Pt. 6. The Mineral Industry in Kansas in 1956. W. H. SCHOEWE. Pp. 179–229; figs. 3; tbls. 41. *Discusses the production and value of all minerals produced in the state in 1956 with comparison with 1955, and includes directories of mineral producers on record as of December 31, 1956.*

Congreso Geológico Internacional, XX Sesión—México, 1956.

Riqueza Minera y Yacimientos Minerales de México (Tercera Edicion). J. G. REYNA. Pp. 479; pls. 18. *Physiography, geology, and mineral deposits of Mexico, with reports on mineral production and exportation, and maps of the locations of deposits. In Spanish.*

Memoria Geologico—Minera del Estado de Chihuahua. J. GONZÁLES-REYNA. Pp. 280; pls. 3; fig. 1. *Physiography, hydrography, and geology of the state. Dis-*

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U. S. Geological Survey—Washington, D. C., 1957–1958.

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Economic Geology
Vol. 55, 1958, pp. 509–510

SCIENTIFIC NOTES AND NEWS

THE AMERICAN INSTITUTE OF MINING, METALLURGICAL, AND PETROLEUM ENGINEERS held a Conference on High-Temperature Materials and Their Resources, sponsored by the Southern California Section of AIME, on May 5 and 6 in Los Angeles. The event was in conjunction with the Molybdenum Fabrication Conference of the Southern California Chapter of the American Society for Metals on May 7 and 8. Subjects included were Mechanical Properties of Refractory Oxides; High Temperature Strength and Creep in Graphite; Strength and Low Temperature Creep; Geology and Resources of Minerals of the High Temperature Metals; Refractory Metals, Tungsten, Molybdenum, Columbium and Nickel; Thermodynamic High-Temperature Objectives; Materials for Containment of High-Temperature Reactions; Geochemistry of Rhenium; The Riddle Nickel Project, Oregon; Geology of the Searles Lake Deposits with Special Reference to Tungsten; Behavior of Ceramics at High Temperature; High-Temperature Structural Properties; Trends in Refractory Metals; High-Temperature Oxidation; Electron Gun Furnace; Mechanical Properties of Ceramics; Strength of Refractory Metals; Slip and Pinning at High Temperature; Physical Properties in the Non-Metallics. At luncheon May 5, DR. JOHN W. VANDERWILT spoke on "The Free World Resources and Economics of the High-Temperature Metals." The banquet speaker on May 5 was PROF. NICHOLAS J. GRANT of M.I.T. whose subject was "A Metallurgical and Philosophical Tour of Russia."

WILLIAM B. HEROY, JR., of the Geotechnical Corp., Dallas, Texas, presented a series of five lectures to the Geology Department at Dartmouth College during the week of April 14–18 on the Application of Geophysics.

RAYMOND THORSTEINSSON of the Canadian Geological Survey, Ottawa, presented a series of lectures at Dartmouth College during the week of March 10 on the Geology of the Canadian Arctic Islands.

JOHN BURGESS, JR., has been named minerals attache of the United States Embassy, Lima, Peru. At one time he was manager of Representacions Generales, and has been an independent mining consultant since 1951.

HANK HOSMER, chief geologist for the Cerro de Pasco Corp., returned recently to the United States after serving seven years in Peru.

ALLAN BOTSFORD, former consultant for the United States government with headquarters in London, England, has returned to the United States after five years and is now engaged in private consulting at San Fernando, Calif.

H. K. CONN, formerly chief geologist in the exploration department of Canadian Johns-Manville Co., Ltd., Asbestos, Canada, has been promoted to exploration manager for the company.

ARTHUR R. KINKEL, JR., of the U. S. Geological Survey, has returned from a two-month study of base metal and iron deposits in Turkey. This study was made at the request of the International Cooperation Administration.

DONALD M. WAGG has been appointed chief geophysicist for Rio Canadian Exploration Ltd., exploration division of Rio Tinto Mining Co., of Canada, Ltd.

RAYMOND G. G. LINDLOF, formerly geological engineer with the AEC in Casper, Wyo., is now chief engineer and geologist for Federal Uranium Corp., Salt Lake City.

WILLIAM M. MCGILL, for many years with the Virginia Geological Survey and for the past ten years state geologist of Virginia, now is engaged in consulting geological work in Charlottesville, Va.

PAUL NORMAN CLAWSON has joined the mining and exploration department of International Minerals & Chemical Corp., Chicago, as a geologist.

The nature and role of ionic complexes in various geochemical processes were explored in a symposium held March 18, 1958, at the U. S. Geological Survey in Washington, D. C. A panel of five scientists spoke on the subject: P. B. BARTON, H. T. EVANS, JR., R. M. GARRELS, T. S. LOVERING, and K. J. MURATA. An audience of 200 participated in a lively discussion following the presentation of current developments and ideas by the panel members. W. T. PECORA, who organized the symposium, stated that publications are in preparation giving experimental and theoretical data to demonstrate the importance of ionic complexes in metal transportation in geologic processes.

EARL INGERSON former Chief of the Petrology and Geochemistry Branch of the U. S. Geological Survey, will join the teaching staff of the University of Texas as Professor of Geology in September 1958, where he will teach elementary geology and advanced courses in geochemistry. Half of his time will be reserved for research in geologic thermometry and other fields of mineralogy and petrology.

The Mining Academy of Freiberg, Germany, held its tenth Mining and Metallurgical Celebration May 28 to 31, with a program of mining, geological and metallurgical papers, and attended by many distinguished guests.

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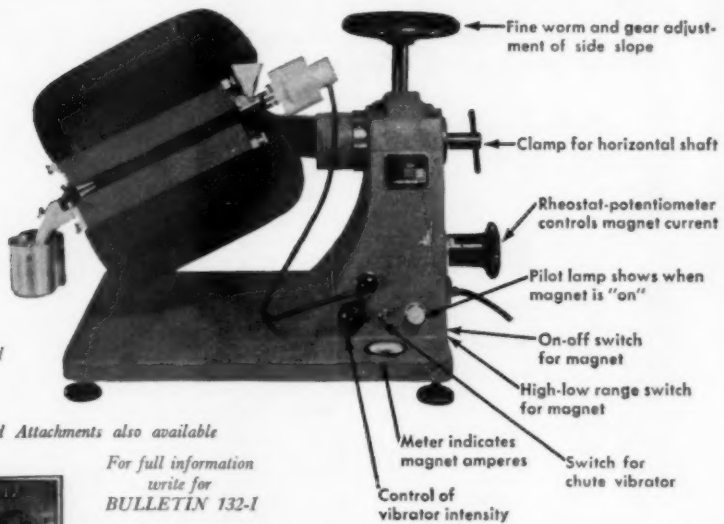
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